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Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Dr Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Vegetation zoning in relation to site and soil properties: A case study in the Darling Range, south-western Australia

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Abstract

In this paper, we describe, using multivariate analysis, the distribution of plant species at three valley-floor sites in the Northern Jarrah Forest, south-western Australia. At each site, plant species are distributed along a topographic gradient in communities that broadly parallel the valley floor, resulting in a conspicuously zoned vegetation pattern. Soils are arranged in a similar pattern, with a clear distinction between upland sandy soils, sandy loams on the footslope and silty loams on the flat valley floor, as reflected by changes in field texture, gravel content, electrical conductivity (EC) and major element concentrations. We found that the predominant influences on plant distribution were waterlogging and gradient, indicating a direct relationship between vegetation and topography. However, the relationship between vegetation and soil was less pronounced. There were moderate correlations between species distribution and the soil properties Texture, Gravel Content and Electrical Conductivity, and weak correlations with soil concentrations of Fe, C and Mn.

We speculate that soil properties at these sites developed in response to the same seasonal conditions of desiccation and waterlogging that currently control plant distribution, albeit at substantially different timescales. Thus, the relationship between vegetation and soil is an indirect one, reflecting the dominant influence of hydrology on the distributions of both plants and soil.

Key words: edaphic controls, jarrah forest, laterite, ordination, soil catena, vegetation mapping, waterlogging.

Introduction

Relationships between rocks/soils and vegetation have been recognised for centuries and used routinely in mineral prospecting and agriculture (Agricola 1556; Lomonosov 1763, cited in Malyuga 1964; Canon 1960; Ellenberg 1988; Brooks 1998). Some plant communities are consistently associated with particular substrates, such as distinctive 'serpentine flora' in many parts of the world (*e.g.* Brooks 1987; Proctor & Nagy 1992; Batianoff & Singh 2001), halophytes on saline soils in arid, inland areas (Pan *et al.* 1998) or the calcicole communities of limestone belts (Grime & Curtis 1976; Ström 1997). In Western Australia, following pioneering biogeographical studies by Diels (1906), Gardner (1944) and Beard (1990), edaphic controls on plant distribution are now generally acknowledged at both regional and local scales. In this paper, we explore the possibility that, in at least some situations, the relationship between plants and their substrate might not be a direct one. Instead, the distribution of both plants and soils might be determined by some as-yet-unrecognised factor(s).

In the Northern Jarrah Forest of the Darling Range, south-western Australia, there is a clear demarcation in both soils and vegetation between uplands and valley floors (Havel 1975; Bell & Heddle 1989). Eucalypt open forest (*sensu* Specht *et al.* 1974) occupies the uplands; valley floors are occupied by woody shrubland. There is a distinctive soil catena, from shallow, gravelly sands overlying lateritic duricrust on the uplands, to deep loams overlying saprolitic pallid clay on the valley floors (Siradz 1985; Churchward & Dimmock 1989). Vegetation within most of the forest appears relatively uniform but, on valley floors, there is a conspicuous zonation of species along a micro-topographic gradient, which seems to reflect local differences in water availability and waterlogging. Preliminary observations identified three broad landscape subdivisions from the forest edge to the lowest part of the valley floor – Footslope, Dry Flat and Wet Flat.

In this study, the 'Footslope' includes the downslope edge of jarrah (*Eucalyptus marginata*) forest, which might properly be regarded as the margin of the forested uplands. The uplands are characterised by gravelly (pisolithic) sands, with scattered outcrops of lateritic ferricrete, while the valley floors are dominated by silty or sandy loams. In many situations, the Footslope is a gently concave, transitional geomorphic unit between the upland and the flat valley floor, but its boundaries are not always clearly defined. Vegetation on the Footslope

is typically a park-like, low shrubland, often with a sparse overstorey of marri (*Corymbia calophylla*) and yarri (*Eucalyptus patens*).

The 'Dry Flat' includes both the edge of the flat valley floor and permanently dry, slightly elevated parts of the flat. The 'Wet Flat' is that part of the valley floor that is subject to periods of waterlogging in winter. It supports a woody shrubland, which varies throughout the study area from dense *Melaleuca* thickets to meadow-like clearings, where low shrubs are interspersed with sedges and annual herbs. The characteristic high proportion of bare ground surface distinguishes the Wet Flat from the adjacent Dry Flat.

Mäckel (1974) introduced terminology to describe hydrological aspects of zoning in southern African dambos. Our 'Footslope' corresponds to Mäckel's 'upper washbelt' and at least part of his 'lower washbelt', while our 'Wet Flat' is equivalent to his 'seepage zone'. However, our category 'Dry Flat' is not recognised in Mäckel's scheme.

This paper examines the distribution of soils and vegetation at three valley-floor sites in the headwaters of Big Brook and within the Northern Jarrah Forest. The study was part of a larger project investigating hydrological properties of valley floors in the Northern Jarrah Forest, in anticipation of planned bauxite-mining trials. We describe the soil catena in detail at only one of the sites, as catenas at these sites appeared almost identical. We also describe the vegetation at each site. By combining plant and soil observations in a single analysis, we address the question: do plants and soils covary in this area, *i.e.* are they distributed in a similar pattern, possibly indicating a common influence? We discuss management implications of our observations.

Methods

Study area

The study area (centred on 32°35'0" S, 116°15'10" E; approximate elevation 270 m) is located in the Darling Range, approximately 70 km SSE of Perth, south-western Australia (Fig. 1). This part of the Darling Range supports jarrah (*Eucalyptus marginata*) forest, as described by Dell *et al.* (1989).

The climate is Mediterranean (Köppen-type *Cs*), with mild, wet winters and hot, dry summers. On average, about 80% of the annual rainfall of approximately 1000 mm falls over the winter rainy season, between May and September (inclusive). Less than 5% falls during the summer months, December – February.

Like other drainage lines in the area, those in the present study are ephemeral streams; surface flow is confined to winter. There is rarely a defined channel. Rather, the flat valley floors are waterlogged during winter across much of their 50–150 m width.

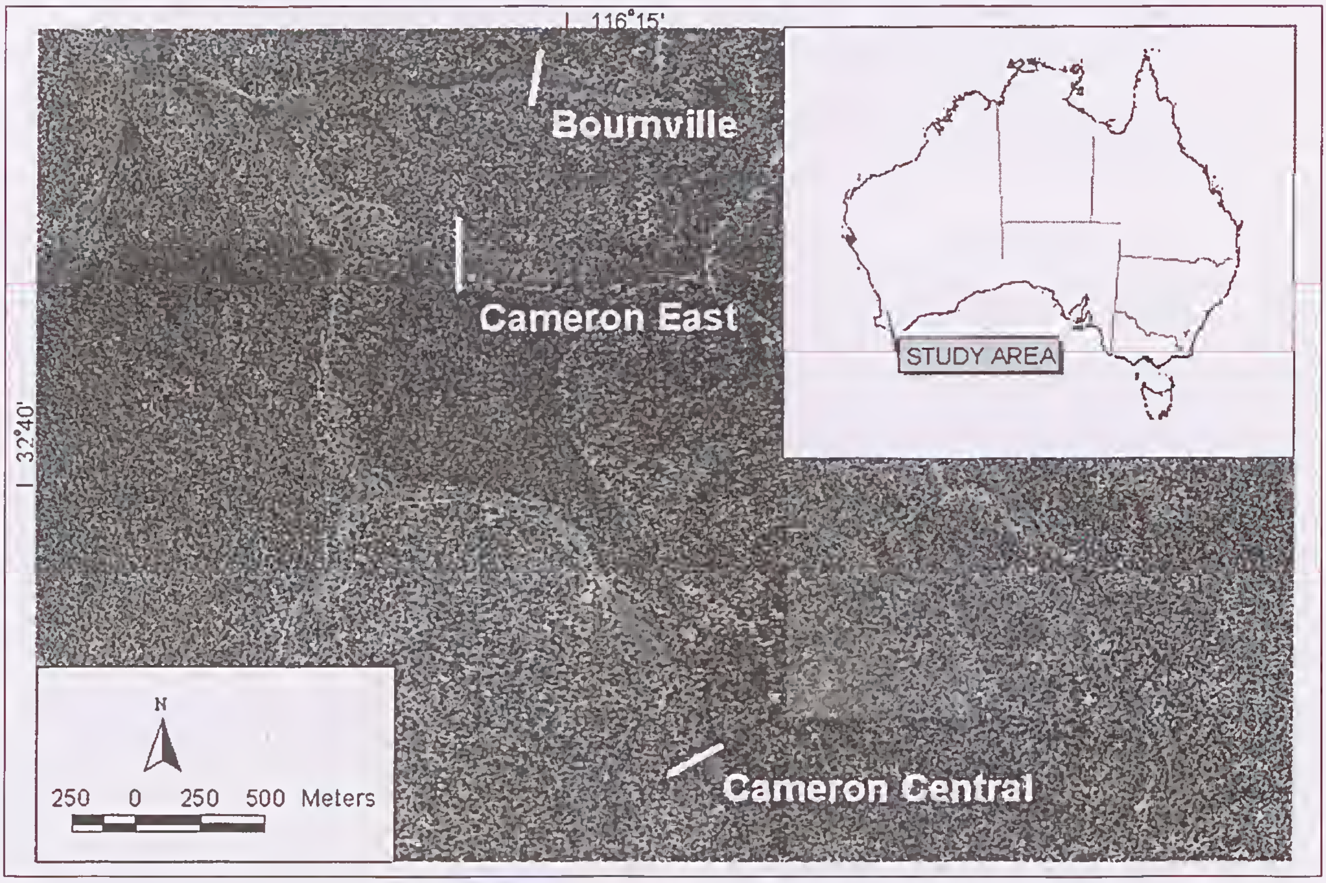

Figure 1. Air photographic mosaic of the study area, showing the three valley-floor study sites Cameron Central, Cameron East and Bournville. Note the pale, fine-textured, sinuous valley floors (often flanked by vehicle tracks), which contrast markedly with the dark, coarse-textured uplands.

Vegetation on the flat valley floors is a shrubland, generally 0.3–1.5 m tall, with scattered trees. The dominant shrub species are *Hakea varia, H. prostrata, H. marginata* (Proteaceae) and *Melaleuca incana* (Myrtaceae), with subdominant *Hypocalymma angustifolium* (Myrtaceae), *Astartea fascicularis* (Myrtaceae) and *Baeckea camphorosmae* (Myrtaceae). The main tree species are yarri (*Eucalyptus patens*; Myrtaceae) and paperbark (*Melaleuca preissiana*; Myrtaceae), with minor flooded gum (*Eucalyptus rudis*; Myrtaceae).

Transect Survey

Site Description

Three first-order, valley-floor sites in the Big Brook catchment, Cameron Central (CC), Cameron East (CE) and Bournville (BO), were selected for this study (Fig. 1). At CC, a 180 x 60 m grid was established, while at CE and BO single transects, 240 m long, were laid out across the valley floor at right angles to the local creekline, extending a short distance into jarrah forest on either side. Stations were spaced at 20 m intervals. There were 53 stations in total – 13 at each of CE and BO, and 27 at CC. Lines were surveyed with a measuring tape and relative heights were measured to the nearest centimetre using a laser level. Gradients between adjacent stations (expressed in degrees) were calculated from their relative heights using trigonometric relations (sine rule).

Each station was assigned a 'waterlogging index'. This was based on regular observations through the 2000 winter (weekly piezometer readings at Cameron Central and Cameron East, and monthly auger drilling at Bournville). The waterlogging index was assigned as: 0 = dry surface in winter, well drained; 1 = dry surface in winter, but subsurface (perched) water table at < 0.5 m depth for ≥ 2 months; 2 = damp surface in winter, subsurface water table at < 0.2 m depth for ≥ 2 months; 3 = muddy/sticky surface in winter, sodden ground (*i.e.* water table at 0 m) for ≥ 2 months, shallow surface water for a few days after heavy rain; 4 = surface water for ≥ 2 months, occasionally flowing.

Vegetation

Each station on the CC grid and the CE and BO transects was designated as the centre for a 100 m^2 (10 m x 10 m) vegetation-sampling quadrat. In each quadrat, the relative abundance of 66 plant species was scored according to the following scheme: 0 = none; 1 = a few (< 10%); 2= some (10–50%); 3 = many (51–90%); 4 = almost all (> 90%). Abundance was estimated visually as the relative proportion of individuals in the quadrat population, rather than as percentage cover, so that a leafless or diminutive species, such as *Acacia incurva* was not necessarily overwhelmed by a large, leafy species, such as *Acacia saligna*. Thus, the assignment of abundance codes was somewhat subjective. However, for consistency, all estimates were made by the same observer (IRF).

The species were selected as those most frequently occurring in valley-floor situations in the Big Brook area. Fifty-five of these species were recorded from at least two quadrats and were included in the analysis (*i.e.* species recorded from only a single quadrat were excluded from statistical calculations). Species were identified from keys in Marchant *et al.* (1987). Nomenclature follows Paczkowska & Chapman (2000).

We emphasise here that our plant list is not intended as a complete floral audit of the sites. Species were selected from the valley-floor flora, based on their 'commonness' in the Big Brook area and their ease of identification (a particularly relevant consideration for a group whose taxonomic skills varied tremendously). Members of the families Centrolepidaceae, Cyperaceae and Restionaceae, as well as the large genus *Lomandra* were not included in the systematic survey, although their presence was sometimes noted informally. The Wet Flat includes a number of annual species that are widespread in the Big Brook area but rarely abundant in a single quadrat. They are not reported in Table 1 because they were not flowering at the time of the survey; their presence is known, however, from earlier visits. Examples are *Utricularia multifida* (Lentibulariaceae), *Drosera* spp (Droseraceae), *Hypoxis occidentalis* (Hypoxidaceae), *Stylidium spp* (Stylidiaceae) and *Stypandra glauca* (Phormicaceae).

Soil

Two soil samples were collected from each of the survey stations: (1) a composite sample collected from five shallow (5 cm deep) holes within 1 m of the station; (2) a subsurface sample, collected from the bottom 20 cm of a 1 m auger hole. Field texture was estimated *in situ*, according to the ribbon method described in McDonald & Isbell (1990). The soil textures we encountered varied from sand through loam to medium clay. For computational purposes, we assigned textural codes, as follows: 1 = sand; 2 = loamy sand; 3 = clayey sand; 4 = sandy loam; 5 = loam; 6 = sandy clay loam; 7= clay loam; 8 = sandy clay; 9 = light clay; 10 = medium clay. Thus, the higher the number, the higher the clay content and the heavier the texture of the soil. To ensure consistency, all texture determinations were performed by the same person (SB).

Colour was estimated for moist samples by reference to standard Munsell colour charts (Kollmorgen Corp. 1975). In this paper, 'Soil Colour' is the 'Redness Rating' (RR) of Torrent *et al.* (1980), a single index that combines all three parameters of the Munsell colour sphere, according to the formula

$$RR = [(10-H)C] / V$$

where V and C are numerical values of Munsell value and chroma respectively, and H is the figure preceding YR in Munsell hue. Thus, H = 10 for 10YR, H = 5 for 5YR and H = 0 for 10R. [The hue R (red) is adjacent to YR (yellowish red) on the Munsell sphere and, by convention, 10R is the immediate predecessor of 1YR on colour charts.]

Soil samples were collected from hand-drilled auger holes in each quadrat in the 2000 summer. After air-drying and passing through a 2 mm sieve, both fractions were weighed to determine gravel content, which consisted mostly of ferruginous nodules and pisoliths. Subsequent analyses used the < 2 mm fraction only. Soil pH was determined using a Cyberscan digital meter (Eutech Instruments) for a 1:5 soil:$CaCl_2$ suspension shaken for 1 h at 25°C. Electrical conductivity (EC) was determined for a 1:5 soil:water slurry.

The < 2 mm samples were finely ground, using a mechanical steel mill. Total carbon and nitrogen contents of the soil were determined by combustion, using a CHN-1000 analyser (LECO Corp., Michigan). Plant-available phosphorus and plant-available potassium were estimated by Colwell's (1963) bicarbonate extraction method. The phosphorus present in soil extracts was quantified using a molybdenum-blue colorimetric method (Rayment & Higginson 1992). Potassium was determined for the same soil extract by atomic absorption spectrophotometry (AAS). Total phosphorus, total potassium, sulphur, magnesium, manganese, calcium and iron concentrations of the soil were determined by x-ray fluorescence (XRF), using pressed pellets of finely ground soil with a wax binder.

Soil Profiles

After an orientation soil survey over the entire upper Big Brook area, the Cameron Central Site was selected as a representative valley floor. A single pit, approximately 4 m long, 1 m wide and 2 m deep, was excavated by backhoe at each of the three topographic locations described above (Footslope, Dry Flat and Wet Flat). An additional pit was excavated at an upland location, about 30 m uphill of the jarrah forest – shrubland boundary. The soil profile exposed in each of these pits was examined and the horizons described *in situ* with regard to colour, texture and structure (McDonald & Isbell 1990).

Water Tables

We obtained the depths to a seasonal perched water table and to the permanent, catchment-wide groundwater table at the Cameron Central site from piezometers. These were installed along a transect across the flat valley floor, with an additional nest of piezometers on the Footslope, near the jarrah forest edge. Piezometers more than 1 m deep were drilled using a truck-mounted, 150 mm-diameter, hollow-auger, drilling rig. Slotted-PVC pipes were installed in the open holes and the annulus of each hole was packed with sand. Cement grout was used to seal the borehole at the ground surface. For piezometers less than 1 m in depth, holes were drilled with hand augers.

Water table depths were measured manually with a measuring tape, from April 2000 to April 2001. Measurements were made at weekly intervals throughout the period June – November, and at monthly intervals during the drier months.

Data analysis

Measured variables were compared between the landscape categories (Footslope, Dry Flat and Wet Flat) by one-way ANOVA, after the data had been appropriately transformed to satisfy requirements for independence of means and variance, as well as for homogeneity of group variances (determined by Cochran's test; Winer 1971) . The following variables required transformation: site gradient, topsoil gravel, topsoil EC, Mn, K, subsoil texture and subsoil EC. Note that the reported means are for untransformed data. Post-hoc comparisons of group means were performed using Spjøtvoll/Stoline tests, which allowed for the unequal sample sizes (Spjøtvoll & Stoline 1973). All univariate and ANOVA calculations were made using Statistica (Version 5.1) software (StatSoft Inc. 1995).

Relationships between the 55 species, 53 quadrats and 26 environmental variables were examined with detrended canonical correspondence analysis (DCCA), using the statistical program CANOCO (Ter Braak 1988). There was no transformation of species, no specification of either species-weights or sample-weights, and no downweighting of rare species. Environmental variables were first range-standardised according to the formula

$$Z_{ij} = (X_{ij} - R_{min\,i}) / (R_{max\,i} - R_{min\,i})$$

where X_{ij} is the i^{th} variable in the j^{th} quadrat, R is the range and Z is the desired range-standardised value. For clarity in presentation, ordination scores for the environmental variables were multiplied by three.

Results

Vegetation

As we have already pointed out (see Fig. 1), valley floors, with their characteristic shrubland vegetation, are clearly distinguished from the forested uplands. Within the valley floors themselves, many plant species are confined to particular topographic levels and plant communities are arranged in zones that correspond to the topographic units described above (Table 1). Boundaries between the communities are occasionally sharp, but are more often gradational over several metres. Many of the plant species listed in Table 1 have distributions that include more than one topographic unit. *Eucalyptus patens*, for example, is a common tree in Footslope and Dry Flat locations at all three sites, and even extends to the Wet Flat at Site CC. The woody shrubs *Hakea varia* and *Melaleuca incana*, are moderately to very abundant on the Wet Flat at all three sites; they are less abundant on the Dry Flat and uncommon on the Footslope.

The Footslope supports the highest species diversity because it includes species such as *Eucalyptus marginata* and *Acacia pulchella* that are characteristic of uplands, as well as typical valley-floor species like *Hypocalymma angustifolium*. Comprehensive diversity indices are not reported in this paper however because, as described in the Methods section, the species surveyed are merely a subset of the total flora.

Soil Profiles

Our detailed soil survey at Cameron Central showed a catena similar to that described for another Darling Range site by Siradz (1985). Typical upland soils beneath the jarrah forest canopy (represented here by Pit 013; Fig. 2A) are gravelly loamy sands, commonly underlain by lateritic duricrust, which is in turn underlain by a considerable thickness of kaolinitic clay (Gilkes *et al.* 1973). Nearby drillholes intersected unweathered bedrock at depths ranging from 20 to 50 m (usually 25–30 m). Valley-floor soils, by contrast, are typically deeper, less gravelly, better structured, more clayey and more brightly coloured. Profiles are well developed, with conspicuous A, B and C horizons. Bright yellowish colours of the hydrated iron oxide goethite near the

Table 1

Plant species (and number of quadrats they were recorded in) listed in descending order of 'commonness' and grouped according to topographic unit (Footslope, Dry Flat, Wet Flat). Species highlighted in grey are entirely or almost entirely confined to a single topographic unit.

Topographic Unit	Species	Family	Average Abundance [1]	Percentage of Quadrats [2]	Av. Abundance X Quadrats [3]	No. of Sites [4]
Footslope (*N*=25)	*Eucalyptus marginata (15)*	Myrtaceae	3.7	60	220	3
	Corymbia calophylla (16)	Myrtaceae	2.4	64	154	2
	Trymalium ledifolium (15)	Rhamnaceae	1.8	60	105	3
	Pimelea ciliata (13)	Thymeleaceae	1.7	52	88	2
	Hakea lissocarpha (14)	Proteaceae	1.2	56	68	3
	Macrozamia riedleii (11)	Zamiaceae	1.0	44	44	3
	Lechenaultia biloba (8)	Goodeniaceae	1.3	32	40	3
	Pentapeltis peltigera (3)	Apiaceae	1.3	12	16	2
	Tripterococcus brunonis (3)	Stackhousiaceae	1.3	12	16	2
	Phyllanthus calycinus (2)	Euphorbiaceae	1.0	8	8	2
	Pimelea suaveolens (2)	Thymeleaceae	1.0	8	8	2
	Eucalyptus patens (15)	Myrtaceae	3.1	60	189	3
	Dryandra nivea (24)	Proteaceae	1.9	96	184	3
	Xanthorrhoea preissii (19)	Xanthorrhoeaceae	1.8	76	140	3
	Hypocalymma angustifolium (20)	Myrtaceae	1.7	80	136	3
	Baeckea camphorosmae (12)	Myrtaceae	1.3	48	63	3
	Melaleuca incana (5)	Myrtaceae	1.6	20	32	1
	Astroloma ciliatum (7)	Epacridaceae	1.0	28	28	3
	Leucopogon nutans (7)	Epacridaceae	1.0	28	28	3
	Persoonia longifolia (7)	Proteaceae	1.0	28	28	2
	Leptomeria cunninghamii (4)	Santalaceae	1.0	20	20	2
	Ptilotus manglesii (5)	Amaranthaceae	1.0	20	20	2
	Hakea varia (3)	Proteaceae	1.0	12	12	2
Dry Flat (*N*=13)	*Hakea prostrata (4)*	Proteaceae	1.5	31	47	2
	Hypocalymma angustifolium (13)	Myrtaceae	2.4	100	240	3
	Eucalyptus patens (8)	Myrtaceae	3.6	53	193	2
	Melaleuca incana (9)	Myrtaceae	2.1	69	147	3
	Hakea varia (8)	Proteaceae	2.0	62	124	3
	Xanthorrhoea preisii (7)	Xanthorrhoeaceae	1.6	54	85	2
	Baeckea camphorosmae (5)	Myrtaceae	2.0	38	76	2
	Dryandra nivea (7)	Proteaceae	1.2	54	63	3
	Astroloma ciliatum (5)	Epacridaceae	1.6	38	61	2
	Acacia applanata (7)	Mimosaceae	1.0	54	54	3
	Leucopogon nutans (5)	Epacridaceae	1.2	38	46	2
	Patersonia occidentalis (3)	Iridaceae	1.3	23	31	2
	Persoonia longifolia (2)	Proteaceae	1.0	15	15	1
Wet Flat (*N*=15)	*Melaleuca preissiana (4)*	Myrtaceae	4.0	27	107	2
	Astartea fascicularis (4)	Myrtaceae	2.3	27	60	1
	Stylidium crassifolium (4)	Stylidiaceae	1.8	27	47	1
	Acacia incurva (6)	Mimosaceae	1.0	40	40	2
	Melaleuca viminea (3)	Myrtaceae	1.3	20	27	2
	Dampiera alata (4)	Goodeniaceae	1.0	27	27	1
	Melaleuca incana (13)	Myrtaceae	2.5	87	220	3
	Hakea varia (14)	Proteaceae	2.0	93	187	3
	Hypocalymma angustifolium (12)	Myrtaceae	1.9	80	153	3
	Eucalyptus patens (5)	Myrtaceae	3.5	38	133	3
	Patersonia occidentalis (8)	Iridaceae	1.0	53	53	3
	Acacia applanata (7)	Mimosaceae	1.0	47	47	2
	Xanthorrhoea preissii (4)	Xanthorrhoeaceae	1.5	27	40	2
	Leptomeria cunninghamii (3)	Santalaceae	1.0	20	20	2
	Dryandra nivea (2)	Proteaceae	1.0	13	13	2
	Persoonia longifolia (2)	Proteaceae	1.0	13	13	1
	Ptilotus manglesii (2)	Amaranthaceae	1.0	13	13	1

[1] Abundance index (0-4) described in text
[2] Percentage of quadrats in which the species is present
[3] This is the property referred to in the text as 'commonness'
[4] Number of sites (Cameron Central, Cameron East, Bournville) at which this species is present

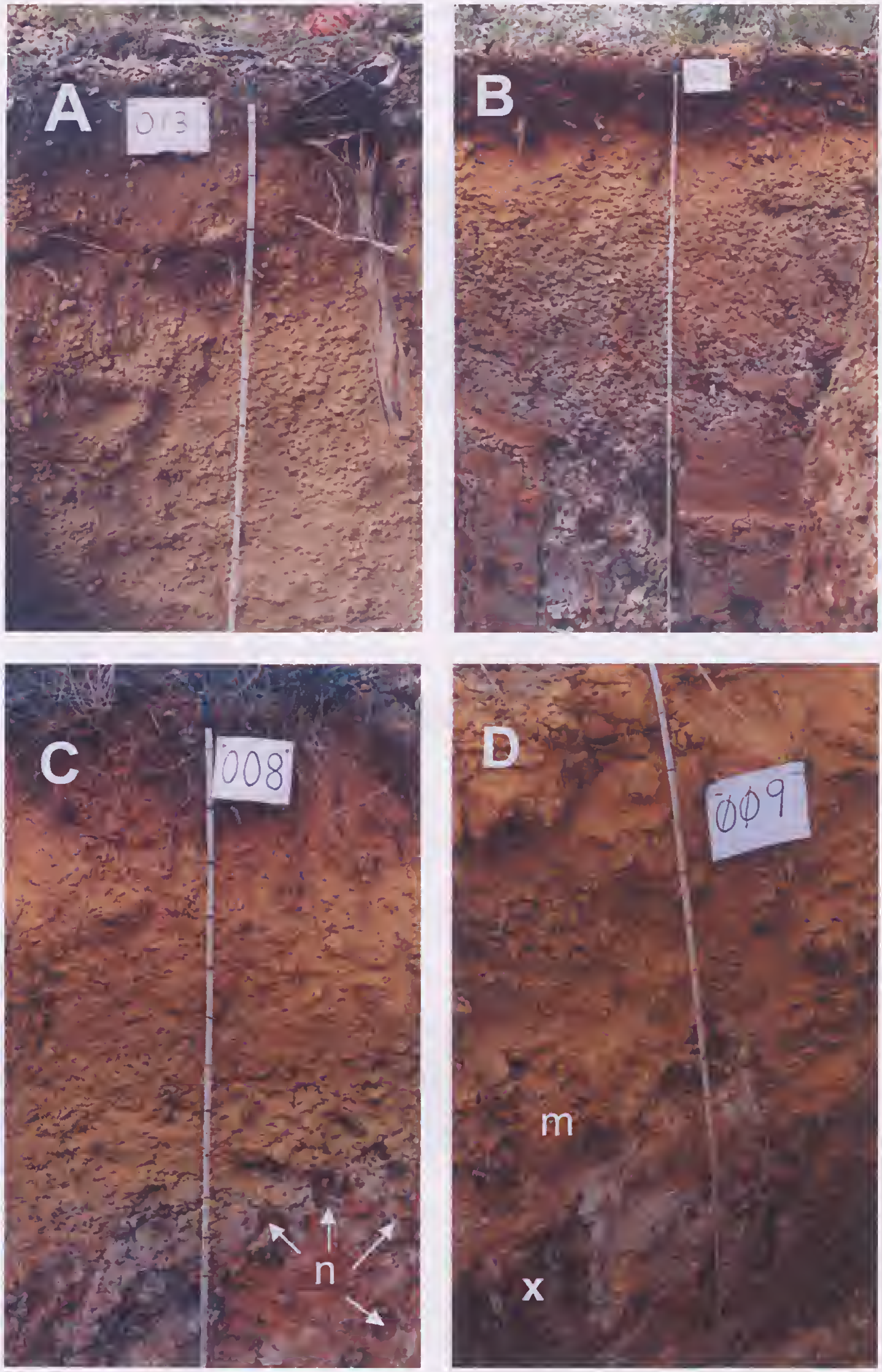

Figure 2. A. Soil profile on an upland forested hillslope adjacent to Site CC (Pit 013). Dull yellowish brown, very gravelly loamy sand. Note rudimentary pedological development and very weak colluvial sorting. The pit floor (not shown) is massive lateritic duricrust. **B.** Soil profile on the Footslope at Site CC (Pit 007). Bright orange sandy loam, passing gradually into dull yellowish brown and reddish brown clay loam, and underlain at about 1.35 m by grey clay. **C.** Soil profile on the Wet Flat at Site CC (Pit 008). Bright yellowish orange silty loam, underlain at about 1.0 m by grey clay. Note irregular nodules (n) of bog iron ore at clay-loam boundary. **D.** Soil profile on the Dry Flat at Site CC (Pit 009). Bright yellowish orange gravelly clay loam and silty loam, underlain by massive (m), becoming columnar (x), bog iron ore. There is an indistinct boundary with grey clay at about 1.55 m.

surface contrast with the dark reds and purples of hematite at depth.

Within the valley-floor environment, footslope soils are readily distinguished from soils of the valley-floor flat. Footslope soils (represented here by Pit 007; Fig. 2B) are sandy loams or clay loams, with abundant pisoliths (presumably derived from eroding duricrust uphill). The flat part of the valley floor, on the other hand, is underlain by silty loam, which has a characteristic brightly coloured, spongy surface. Gravel content is less than 5% at the surface, increasing to 20–50% at depth (Pit 008; Fig. 2C). This increase in the proportion of > 2 mm material (gravel) is due mostly to the *in situ* growth of ferruginous micro-nodules, rather than to the presence of colluvial pisoliths.

At CC and at many other valley-floor sites in the study area, irregular lumps or columns of bog iron ore have developed at the soil-clay interface or in the horizon above it. Within the Dry Flat portion of the CC grid area, massive bog iron ore forms a more-or-less continuous pan across the valley floor flat (Pit 009; Fig. 2D).

Figure 3 is a schematic cross-section across the valley floor at Site CC, illustrating the general relationship between vegetation, soil and topography. A similar catenary situation exists at the other sites. Whereas vegetation is clearly zoned at each of the three sites (CC, CE and BO) and there is a consistent relationship between vegetation and topography, there is no unique (one-to-one) relationship between either soil and topography or soil and vegetation. Furthermore, boundaries between soil units are generally gradational.

This diagram illustrates an important point – valley-floor soils in the Darling Range are not all derived from identical parent materials. Even at the same site, as shown here, some parts of the Footslope are developed on lateritic duricrust, while other parts are underlain by pallid sandy clay. On the flat portion of the valley floor, soils are developed on various parts of the pre-existing laterite profile (usually, but not always, the pallid sandy clay), and include varying proportions of alluvial and colluvial material. In addition, there are authigenic minerals that have crystallised relatively recently, in response to the repeated wetting/drying conditions (Dixon & Weed 1977).

Soil Transects

Analysis of variance showed that there were significant differences in site and soil properties between topographic units (Table 2). Only one property, waterlogging index, was significantly different for all topographic units. The remainder showed similarities between two or all three of the units, which was consistent with our observation that soil changes were often gradual between units. For example, at CC, the typical upland soil encountered in Pit 013 encroached at least 10 m downhill onto the valley-floor Footslope unit.

Table 2

Mean values and standard error (S.E.) of site and soil properties for the three topographic units (Footslope, Dry Flat, Wet Flat). Numbers in each row followed by the same superscript letter are not significantly different.

	Property	Units	Mean Footslope (N=25)	S.E.	Mean Dry Flat (N=13)	S.E.	Mean Wet Flat (N=15)	S.E.
Site:	Gradient	degrees	3.3	0.3	0.71^{a}	0.1	0.34^{a}	0.08
	Waterlogging Index [1]	code (0-4)	0.32	0.09	1.8	0.1	3.0	0.1
Topsoil:	Field texture [1]	code (0-10)	3.6^{a}	0.3	4.5^{ab}	0.1	4.7^{b}	0.2
	Colour [1]		2.5^{a}	0.1	0.5	0.04	2.6^{a}	0.2
	Gravel (wt)	%	46	4	9.5^{a}	2	14^{a}	3
	pH (in $CaCl_2$)		4.8^{a}	0.1	4.4^{b}	0.05	4.6^{ab}	0.1
	Electrical Conductivity	µmS cm^{-1}	54^{a}	4	59^{a}	6	83	9
	C	%	5.9^{a}	0.4	5.6^{a}	1.0	7.4^{a}	0.8
	N	%	0.29^{a}	0.04	0.40^{a}	0.08	0.38^{a}	0.05
	Available P	ppm	7.3^{a}	1.1	5.4^{a}	1.5	5.6^{a}	0.9
	Available K	ppm	91^{a}	11	85^{a}	17	114^{a}	15
	Fe	%	5.8^{a}	0.7	4.6^{a}	1.1	6.5^{a}	0.9
	Mn	%	0.060^{ab}	0.010	0.022^{a}	0.004	0.087^{b}	0.026
	Ca	%	0.31	0.03	0.16^{a}	0.03	0.20^{a}	0.02
	K	%	0.14	0.01	0.23^{a}	0.03	0.28^{a}	0.03
	S	%	0.058^{a}	0.008	0.08^{ab}	0.01	0.11^{b}	0.01
	P	%	0.028^{a}	0.002	0.021^{a}	0.003	0.024^{a}	0.003
	Si	%	19^{a}	1	24^{a}	3	21^{a}	2
	Al	%	8.4^{a}	0.5	6.6^{a}	0.6	6.7^{a}	0.5
	Mg	%	0.098^{a}	0.005	0.09^{a}	0.01	0.11^{a}	0.01
Subsoil:	Field texture [1]	code (0-10)	4.2^{a}	0.3	6.2^{ab}	0.7	6.4^{b}	0.7
	Water	%	12^{a}	1	13^{ab}	1	15^{b}	1
	Colour		5.5^{a}	0.2	1.4	0.1	4.2^{a}	0.3
	Gravel (wt)	%	68^{a}	3	41^{b}	6	54^{ab}	5
	pH (in $CaCl_2$)		4.8^{a}	0.1	4.4^{a}	0.1	4.6^{a}	0.2
	Electrical Conductivity	µmS cm^{-1}	35^{a}	3	58^{a}	6	193	61

[1] See text for description

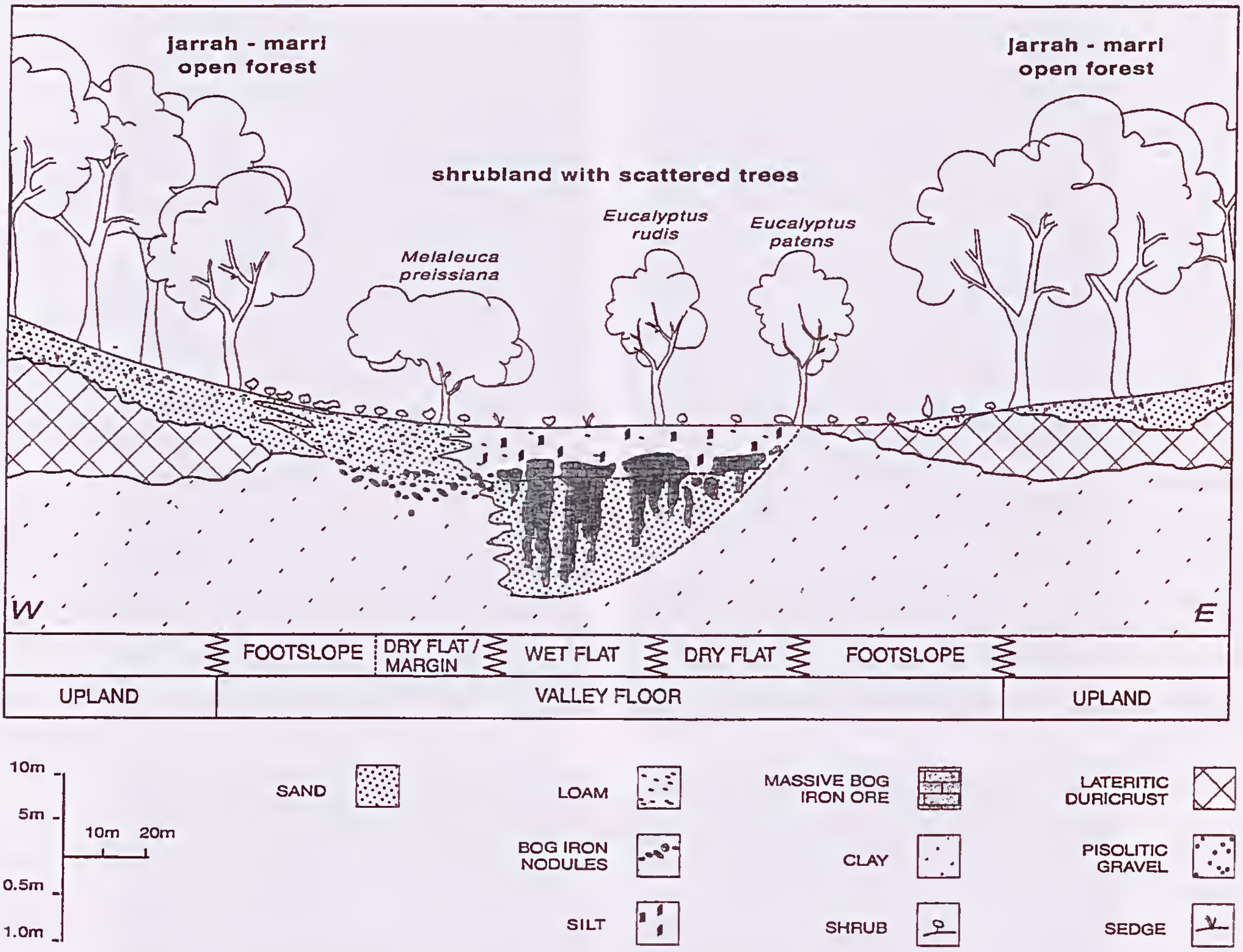

Figure 3. Schematic cross-section across the valley floor of the Cameron Central site, showing relationships between vegetation zoning, soil and topography. Note the vertical exaggeration and the difference in vertical scales between above-ground and below-ground features.

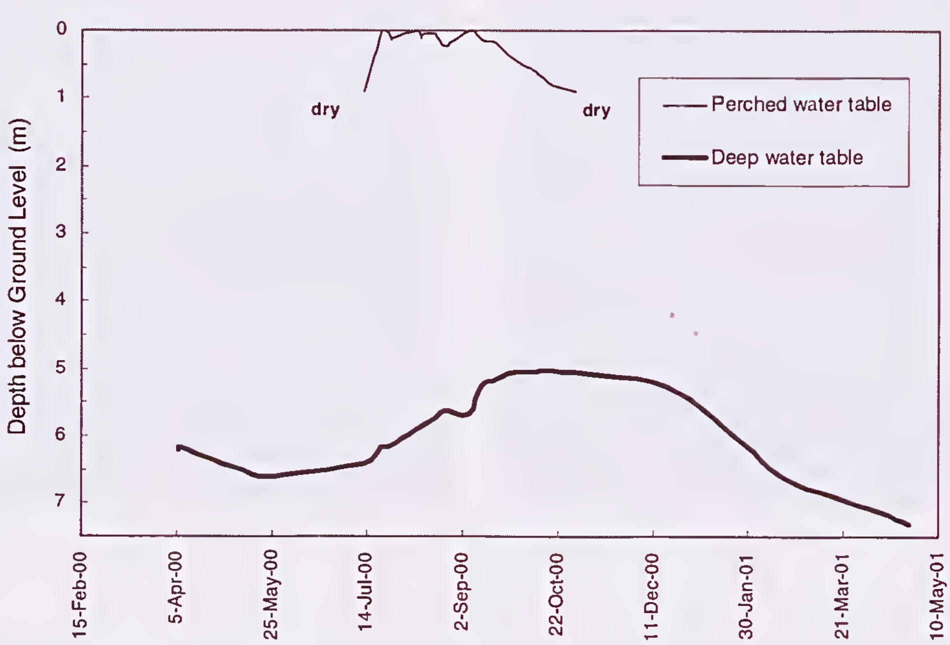

Figure 4. Depths of perched water and groundwater tables at Site CC.

Water Tables

Water levels in two of the CC piezometers (both located on the Wet Flat, near the southern edge of the grid) are shown in Fig. 4. The local catchment groundwater table fluctuated during the study period between 7.1 m and 5.1 m, maintaining its peak level (*i.e.* its shallowest depth) through spring and early summer. This groundwater table was identified in numerous drillholes throughout the Cameron Central catchment, and water tables at similar depths and with similar seasonal fluctuations were recorded in neighbouring catchments throughout the Big Brook area (Ken McIntosh, Alcoa hydrologist, pers. comm.).

The perched water table was confined to winter months on the flat part of the valley floor. At Site CC, this perched water table did not extend across the entire flat, but was confined to the western sector. We observed similar, localised, perched water tables on all drainage lines in the Big Brook area, and believe that these are characteristic features of valley floors throughout this part of the Northern Jarrah Forest.

Ordination

Detrended canonical correspondence analysis clearly separated both quadrats and species of the Footslope from those of the Wet Flat (Figs 5 and 6). This separation was most pronounced on the first ordination axis. Quadrats and species of the Dry Flat occupied a transitional position on the primary axis; their separation was most pronounced along Axis 2. Figure 7A shows the position in the same ordination space occupied by environmental variables. Table 3 lists correlation

Table 3

Correlation constants (Pearson's product moments) between environmental variables and DCCA axes.

	Property	DCCA Axis 1	DCCA Axis 2
Site:	Gradient	-0.72	-0.02
	Waterlogging Index	0.85	-0.05
Topsoil:	Field Texture	0.48	0.07
	Colour 0.00	-0.35	
	Gravel (wt)	-0.74	-0.06
	pH (in $CaCl_2$)	-0.42	-0.42
	Electrical Conductivity	0.34	-0.38
	C	0.09	-0.44
	N	0.27	-0.36
	Available P	-0.11	-0.26
	Available K	0.10	-0.17
	Fe	0.03	-0.44
	Mn	0.03	-0.31
	Ca	-0.50	-0.32
	K	0.55	0.47
	S	0.42	-0.40
	P	-0.25	-0.47
	Si	0.22	0.26
	Al	-0.40	0.00
	Mg	0.09	0.23
Subsoil:	Field Texture	0.46	0.36
	Water	0.33	-0.09
	Colour	-0.18	-0.12
	Gravel (wt)	-0.32	-0.20
	pH (in $CaCl_2$)	-0.32	-0.06
	Electrical Conductivity	0.56	-0.01

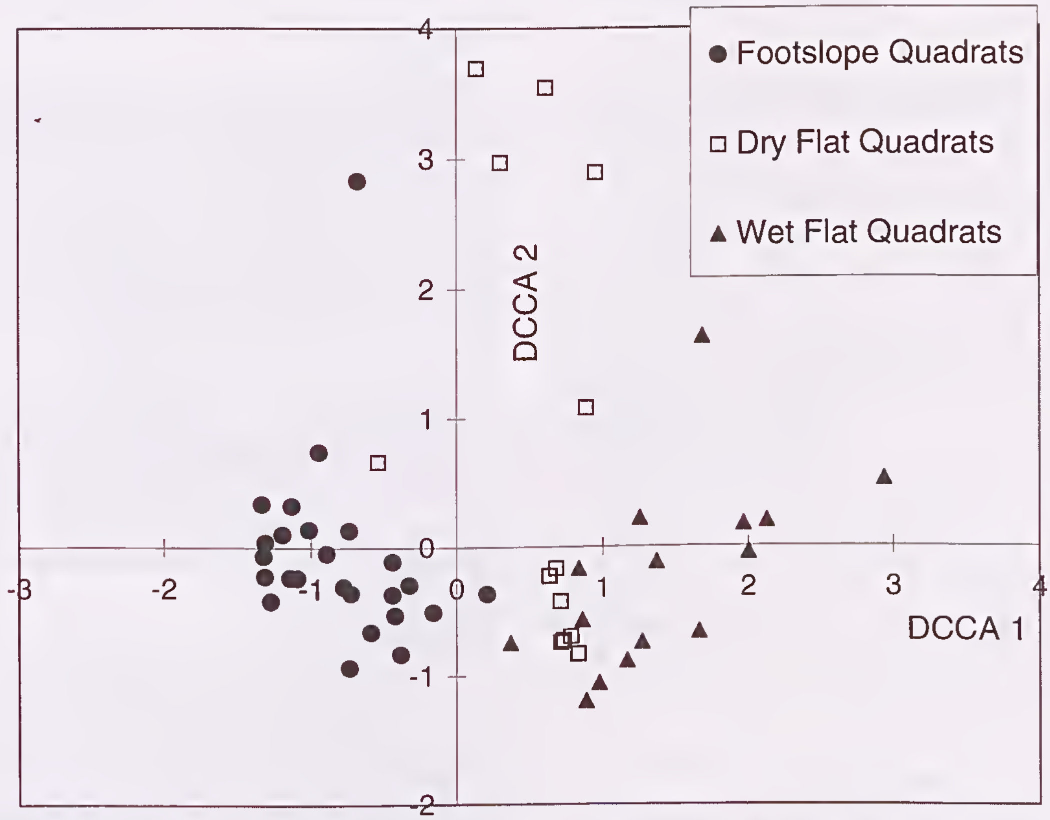

Figure 5. Detrended canonical correspondence analysis ordination of all 53 quadrats at all three study sites combined. Eigenvalues: axis 1 = 0.486; axis 2 = 0.330.

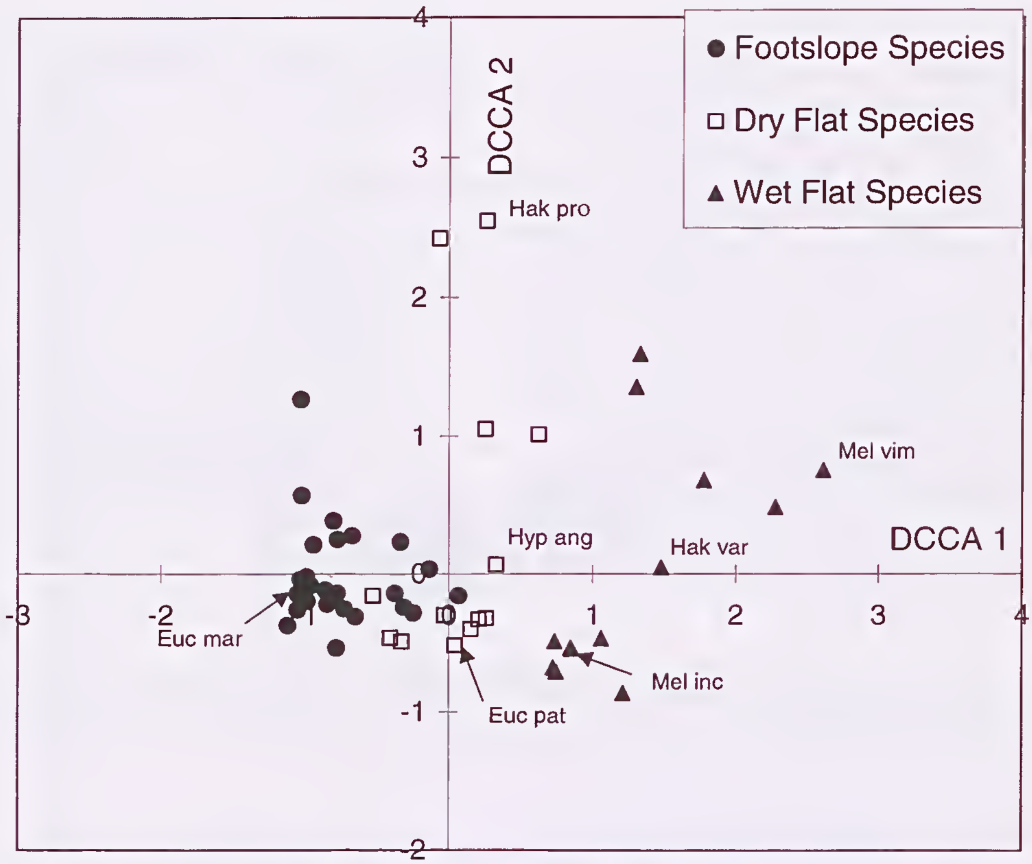

Figure 6. Detrended canonical correspondence analysis ordination of all 55 species. Eigenvalues: axis 1 = 0.486; axis 2 = 0.330. Note that species were assigned to the topographic unit in which they were most commonly recorded. Euc mar = *Eucalyptus marginata* (jarrah); Euc pat = *Eucalyptus patens*; Hak pro = *Hakea prostrata*; Hak var = *Hakea varia*; Hyp ang = *Hypocalymma angustifolium*; Mel inc = *Melaleuca incana*; Mel vim = *Melaleuca viminea*

constants for relationships between environmental variables and the first two DCCA axes. There were strong correlations between several environmental variables and the first axis (r_{max} = 0.85), but the second axis produced correlations of only moderate strength (r_{max} = 0.47).

As summarised in Figure 7B, Axis 1 is associated with variation in the site properties Gradient and Waterlogging Index, as well as the soil physical properties of Field Texture, Topsoil Gravel and Subsoil Water Content. Secondary variation on Axis 2 is associated with the soil chemical properties Iron, Carbon and Manganese, and the related entity Colour (Redness Rating).

Much of the variation on DCCA Axis 2 was associated with Site CE, particularly with Dry Flat quadrats containing the shrub species *Hakea prostrata* (Proteaceae). The association of DCCA Axis 1 with waterlogging owes much of its strength to the winter-wet valley floor at Site BO, which supports a number of species rarely seen at other sites, *e.g. Acacia incurva* (Mimosaceae), *Astartea fascicularis* (Myrtaceae) and *Melaleuca viminea* (Myrtaceae).

Discussion

The ordination described here confirmed our preliminary hypothesis that the distribution of both vegetation and soils on Darling Range valley floors is correlated with topography and waterlogging. On the basis of both vegetation and site/soil properties, valley floors could be subdivided into the three units informally identified before the survey — Footslope, Dry Flat and Wet Flat. This same pattern was reproduced at sites on at least three neighbouring drainage lines — Cameron Central, Cameron East and Bournville — despite the fact that the three sites had slightly different soils and supported some different plant species.

This Wet Flat – Dry Flat dichotomy is a general feature of valley floors in the Big Brook region. In fact, we observed localised winter-waterlogging on drainage lines throughout the Darling Range. Waterlogged areas support a distinctive vegetation of swamp-loving woody shrubs and winter-flowering annual herbs. By contrast, few species are confined to (or even most abundant on) the Dry Flat (see Table 1).

Although sharp boundaries between topographic units can be observed at some localities, there is considerable overlap in most situations in both vegetation and environmental properties. This is reflected in the imprecise borders between units in the quadrat/species ordination (Figs 5 and 6), the many plant species shared between adjoining units (Table 1), and the absence of significant differences between units for many soil properties (Table 2).

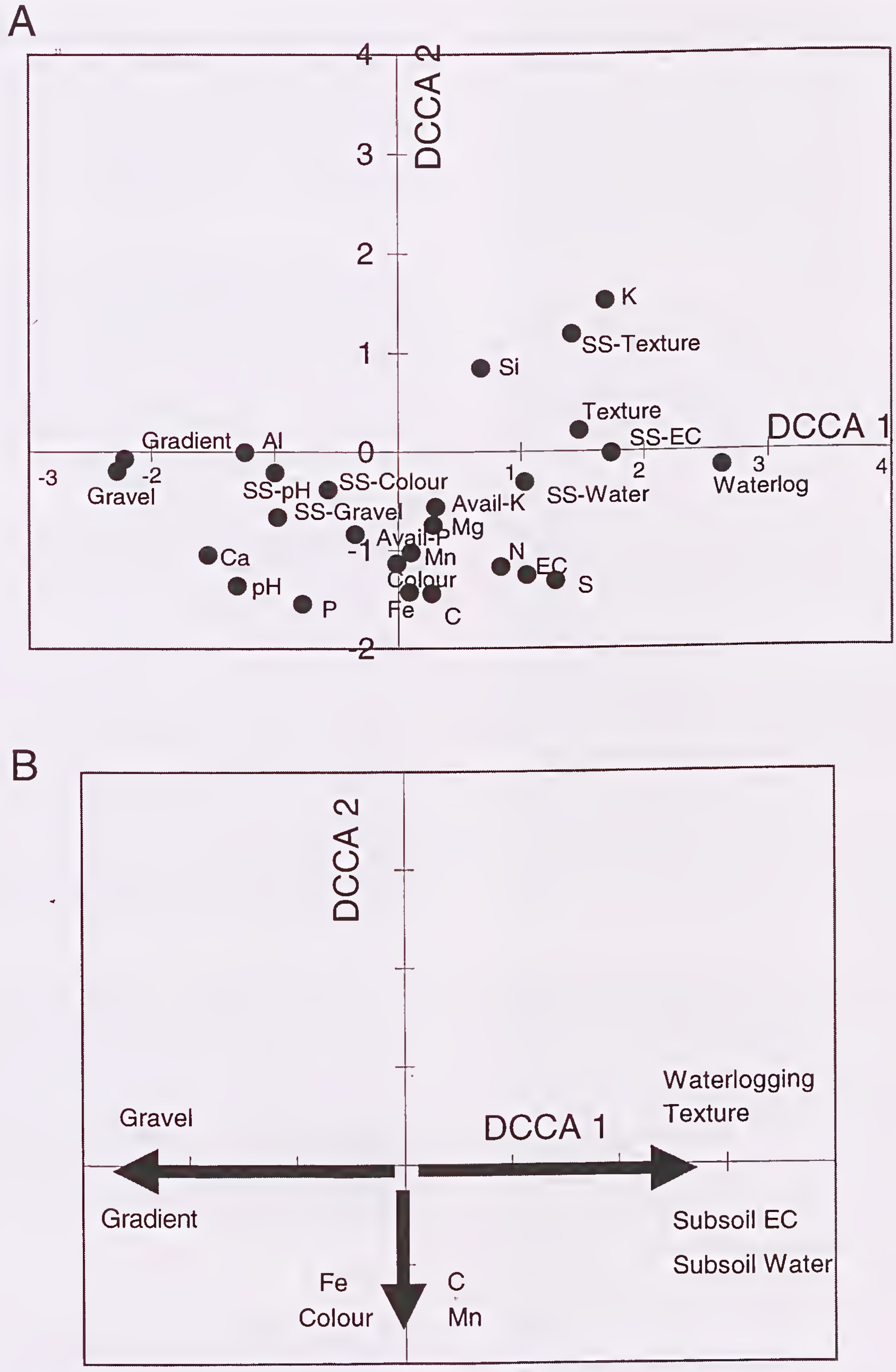

Figure 7. A. Detrended canonical correspondence analysis ordination of all 26 environmental variables. Eigenvalues: axis 1 = 0.486; axis 2 = 0.330. The prefix 'SS' denotes subsoil. Texture = field texture (an approximation of clay content). Waterlog = waterlogging index (see text). **B.** Summary of DCCA ordination in Fig. 7A, showing the main relationships between the ordination axes and environmental variables. Axis 1 is associated with variation in the site properties Gradient and Waterlogging Index, as well as the soil physical properties Field Texture, Subsoil Water Content and Subsoil EC. Axis 2 is associated with the soil chemical properties Fe, Mn, C, and Colour (Redness Rating).

We note that the variables Gravel and Gradient are close together in the Footslope region of the ordination space. High contents of gravel (> 2 mm material) on the slopes can be attributed almost entirely to lateritic pisoliths (see Fig. 2A). Although ironstone is also present on the flat part of valley floors (as bog iron ore), its contribution to the gravel fraction is substantial only in the subsoil. It is interesting that total Al (aluminium) in the soil lies near *Eucalyptus marginata* (jarrah) in the ordination diagram (both plot near –1,0 on Figs 6 and 7(a)). This is not inconsistent with the anecdotal observation that the richest bauxite deposits are found in high-quality jarrah forest.

Levels of plant-available (*i.e.* bicarbonate-extractable) P and K are very low. This has an important influence on the floristic composition of valley floors. Only those species (such as members of the family Proteaceae, with their characteristic proteoid roots; Jeschke & Pate 1995) that are able to tolerate a low P-K environment, are present.

The environmental variable which probably has the strongest influence on plant and soil distribution on valley floors is waterlogging. The waterlogging index used in this paper, a relative measure of the duration of waterlogging, identifies those parts of the valley floor with a perched water table in winter. Adaptations to waterlogging in wetland plants have been reviewed by Armstrong *et al.* (1995) and Crawford (1996), and some Australian examples have been described by Jolly & Walker (1996), Akeroyd *et al.* (1998) and Denton *et al.* (1999). Our observations in Darling Range plants have not been detailed enough to allow us to contribute to the discussion on waterlogging tolerance. However, some general features of the valley-floor vegetation can be identified: (1) there are many woody shrub species and few trees, (2) the dominant vegetation is shrubland, and (3) valley floors appear as gaps in the jarrah-dominated regional forest cover. The sensitivity of jarrah roots to even intermittent waterlogging has been described by Davison (1988).

The first two ordination axes account for only 31.4% of the variance in the species-quadrat-environmental variable relationship. Okland (1999) found that canonical correspondence analysis regularly underestimates this percentage. Nevertheless, it seems likely that other factors, not measured in our survey, were influencing plant distribution on Darling Range valley floors. Possible influences include fire, *Phytophthora* dieback and increased sedimentation associated with logging and road construction in adjacent uplands (Abbott & Loneragan 1983; Dawson *et al.* 1985; Borg *et al.* 1987; Stoneman *et al.* 1987; Bell *et al.* 1989). Historical records (Western Australian Department of Conservation and Land Management, Dwellingup, pers. comm.) indicate that Site CC had indeed burned (albeit patchily) three years before the survey (*i.e.* 1997). Air photos suggest that much of the CE and BO valley floors had been burnt at least once in the early-mid 1990s. However, in the three-year period that we visited these sites, we noted no consistent changes in the vegetation that might be interpreted as a recovery trend from disturbance.

The relationship between vegetation and topography is essentially related to differences in water availability, whereas soils are related not just to topography but also to parent materials. The relative sharpness of the relationship between vegetation and topography, compared with the fuzziness of relationships between both soil-and-topography and soil-and-vegetation, can probably be attributed to difference in timescales between the establishment of a plant community and the formation of a soil. Plants arrange themselves into communities over hundreds of years or decades, whereas the pedological processes that take place during soil formation may require thousands of years or longer to achieve an equilibrium state. The present laterised landscape of the Darling Range is thought to have existed since at least mid-Tertiary times (20–30 million years ago; Anand & Paine 2001). However, there have been major changes in the climate and vegetation of southwestern Australia during that interval (Frakes 1999; Frakes & Barron 2001). By comparing the distribution of fossil pollen of South-West forest trees with their present rainfall requirements, Churchill (1968) identified shifts in the hydrological regime over the past six thousand years. Such very recent hydrological changes would not necessarily be reflected in the soil.

By analogy with other areas in the Darling Range and from the results of in-house, hydrological modeling (Croton & Bari 2001; Croton & Barry 2001), it is anticipated that bauxite mining, with its attendant forest clearing, could result in increased levels of runoff and drainage. This, in turn, would lead to increases in the extent and/or duration of waterlogging on valley floors, an increase in the proportion of Wet Flat over Dry Flat environments, and changes in the floristic composition of valley-floor vegetation. Although bauxite ore is generally absent from valley floors and there is no intention to mine valley floors themselves, some transient 'collateral damage' (*e.g.* haulage roads, turnaround areas) will inevitably take place. Our work shows that species selection for the rehabilitation of such damaged areas should be informed, not by maps of soil distribution or pre-mining vegetation, but by post-mining waterlogging patterns.

An additional feature of valley floors in the Darling Range, which has not been explicitly examined in the present study, but which may nevertheless have a prominent role in determining plant distribution, is the summer insolation. Because valley floors are often treeless and canopy cover tends to be lower than in adjacent forest, they are exposed to full summer sun and drying winds. Claypans are commonly characterised by cracking surfaces and patches of bare ground. The vegetation inhabiting such places must be capable of tolerating periodic desiccation as well as seasonal waterlogging.

Conclusion

We conclude, from the transect data, that the predominant influences on plant distribution across valley floors in the Big Brook area of the Darling Range are the site properties Waterlogging and Gradient. There were also strong correlations between vegetation and the soil properties Field Texture, Gravel Content, Electrical Conductivity (EC) and some major element concentrations. Our data are insufficient to imply causal relationships; however, we speculate that these soil

properties have developed in response to the same seasonal conditions of desiccation and waterlogging that currently control plant distribution on these valley floors. Pedogenesis takes place over a timescale of many thousands (possibly millions) of years, rather than the hundreds of years or decades required to establish plant communities. It is suggested that any proposed developments on these valley floors should consider changes in the local hydrology.

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The hydrology and hydrochemistry of six small playas in the Yarra Yarra drainage system of Western Australia

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Abstract

The hydroperiod, filling frequency, local shallow groundwater movement and surface water and shallow groundwater chemistry of six small (< 3km^2) playas from the Yarra Yarra drainage system of Western Australia were monitored from September 2002 to June 2004. The playas are morphometrically similar and adjacent and represent a hydrological continuum of ephemeral basins ranging from mostly wet (Mongers B) to mostly dry (Kadji A). Hydroperiod ranged from 19 to > 211 days and filling frequency from 1 to 3 cycles over the study period, reflecting rainfall and sub-catchment variability. The playas are net discharge points for groundwater. However, small local vertical head variations suggest that groundwater does not discharge at the same rate across the playa surfaces and that playas may have short-lived recharge phases. Chemically, the playas are typical of salt lakes in Australia. Surface waters showed an ionic dominance consistent with seawater with minor variations attributed to transitional phases in the geochemical evolution of the waters. Shallow ground waters showed a common and consistent pattern of ionic dominance: $Na^+ > Mg^{2+} > K^+ > Ca^{2+} : Cl^- > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$. A geochemical pathway of brine evolution is proposed.

Keywords: hydroperiod, Yarra Yarra, playa, hydrochemistry, ground water

Introduction

The hydrology and hydrochemistry of six small playas in the Yarra Yarra drainage system of Western Australia were investigated between September 2002 and June 2004. Serious catchment degradation, including modifications to catchment hydrology and hydrochemistry through secondary salinisation and related processes threatens the ecology of the lakes (Williams 1999; Clarke 2001; Clarke *et al.* 2002; Boggs *et al.* in press). It is clear that the naturally occurring playas of the Yarra Yarra drainage system are ecologically important wetlands which perform crucial structural and functional roles for the wider Yarra Yarra catchment. These include supporting a diverse suite of aquatic organisms as well as providing habitat to rare migratory birds. Several unique and rare organisms are known to inhabit the lakes including a new species of giant ostracod (Crustacea) *Australocypris mongerensis* (Halse & McRae 2004) and the rare wading bird, the hooded plover (*Thinornis rubricollis tregellasi* Mathews, 1912) (Marcus Signor, pers comm.) which is listed on the 2006 IUCN Red List Category as a near threatened species (BirdLife International 2006). Additionally, the playas may have significance for human well-being and economy. It is therefore important to understand their structure and function.

Playa hydrology, particularly variations in hydroperiod, whether linked to climate and catchment variation and/or anthropogenic modifications has implications for playa ecology through water chemistry characteristics such as salinity and ionic composition (Williams *et al.* 1990; Saros & Fritz 2000a; Radke *et al.* 2003), including the prevalence of waterbirds (Halse *et al.* 1994; Chapman & Lane 1997; Roshier *et al.* 2001, 2002), the distribution of macrophytes (Brock & Lane 1983) and invertebrate populations (Williams 1998). It also influences lake morphology through surface water shaping processes (Bowler 1986; Timms 1992; Boggs *et al.* 2006). Groundwater movement and groundwater – surface water interactions are also an important control of both playa morphology (Bowler 1986) and the chemical evolution of lake brines (Bowler 1986; Torgersen *et al.* 1986; Jankowski & Jacobson 1989).

Thus, given the importance of playa hydrology and hydrochemistry to many aspects of the playa environment, the main objectives of this research were to: relate patterns of hydroperiod and filling frequency and to rainfall and catchment characteristics; characterise local, shallow groundwater movement; and measure variability in surface water and shallow groundwater chemistry.

Setting

The Yarra Yarra drainage system is located in the Yarra Yarra catchment approximately 300 km north-east of Perth, Western Australia (Fig. 1). Stretching for over 300 km, the drainage line is comprised of a chain of over 4, 500 interconnected playa lakes (Boggs *et al.* 2006). In the lower Yarra Yarra drainage system, small playas, *i.e.* those with an area < 10 ha, constitute 51% of the total number of playas reaching spatial densities of > 15 playas/km^2 (Boggs *et al.* 2006). They are highly responsive to rainfall and runoff events and show great variability in hydroperiod across the catchment. Thus the research presented here focuses on this type of wetland.

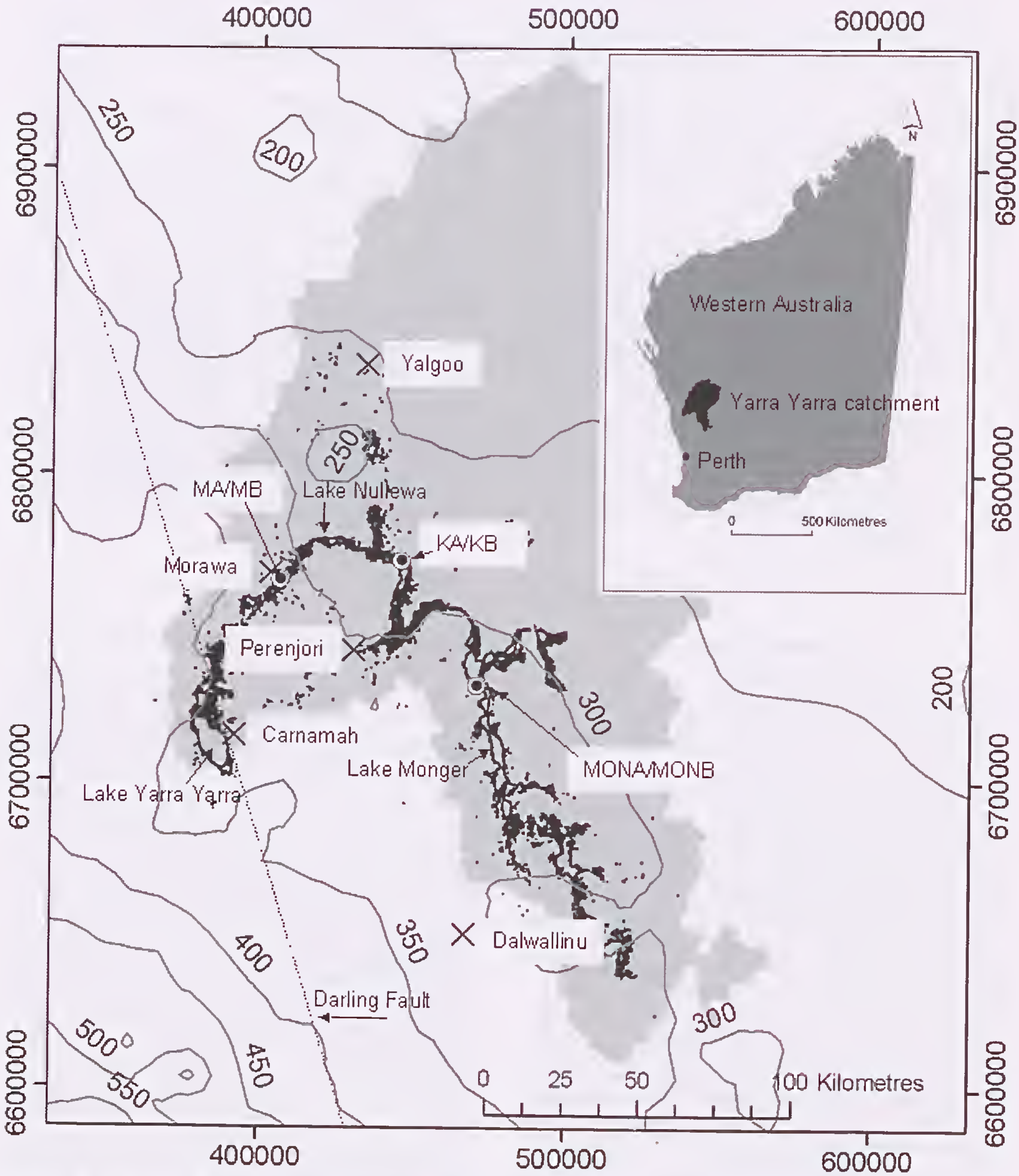

Figure 1. The location of the Yarra Yarra catchment in Western Australia showing the location of the study playas in the Yarra Yarra drainage system; annual rainfall isohyets (data derived from Taylor, 2001) and climate averages at three locations in the Yarra Yarra catchment; (a) Yalgoo; (b) Morawa; and, (c) Carnamah (data from Bureau of Meteorology, 2004).

Geomorphology and geology

The evolution of the modern Yarra Yarra drainage system began in the Pliocene (Yesertener 1999). Due to a combination of tectonic uplift and increasing climatic aridity, the palaeodrainage became landlocked and has became progressively saline (Beard 1999, 2000) through the concentration of aerosol salt from the sea (Chivas *et al.* 1991). Detailed accounts of the geomorphology of the Yarra Yarra system are given in Killigrew & Gilkes (1974), Beard (1999; 2000) and Boggs *et al.* (2006).

Surficial alluvial and lacustrine sand and clay of ~5 m thickness overlay Tertiary palaeochannel deposits in the Yarra Yarra salt lake valley (Commander & McGowan 1991). The catchment is divided into two major geologic subdivisions by the Darling Fault: sedimentary lithology to the west and Achaean granite and granitic gneiss to the east (Flint *et al.* 2000).

Climate

The Yarra Yarra region is characterised by hot, dry summers and warm, wet winters (Gentilli 1971, 1993) (Fig. 1). Annual average temperatures range from 12.5 – 27 °C and the annual average evaporation rate is approximately 2000 mm (Bureau of Meteorology 2004). Reliable rainfall occurs between May and September, although localised thunderstorms and cyclones can bring heavy summer and autumn precipitation (Henschke 1989; Yesertener *et al.* 2000). For example, above average annual rainfall occurred in the region in 1999 with 46% of the total rainfall recorded at Carnamah falling during the autumn months (Bureau of Meteorology 2004). Annual average rainfall ranges from 200 – 400 mm across the catchment, becoming progressively drier from southwest to northeast (Fig. 1). This rainfall gradient creates variability in lake hydroperiod across the catchment area. This has not been systematically evaluated, however observations of the authors and others (Brock & Lane 1983; Henschke 1989) indicate that hydroperiod is generally short, usually only a few weeks in duration.

Groundwater

Groundwater underlies the entire catchment at variable depths and the watertable tends to follow the topography (Henschke 1989; Clarke 2001). Depth to groundwater is generally less than 10 m (Commander & McGowan 1991) in the dominant granite and gneiss geology (Flint *et al.* 2000) and fluctuates in response to seasonal rainfall (Speed & Lefroy 1998; Speed 2001a, b). These groundwaters progressively increase in salinity, to > 200 g/L and rise to within 2 m of the surface with increasing proximity to the salt lakes (Commander & McGowan 1991).

Groundwater flow is from the flanks of the valley towards the chain with an inferred component of flow downstream, *i.e.* from Lake Mongers to Yarra Yarra with each playa acting as a discharge site. Yesertener (1999) investigated the groundwater discharge from Lake Yarra Yarra and concluded that the groundwaters are linked to the Moore catchment and active Moore River to the south through the underlying Tertiary palaeochannel aquifer.

Hydrochemistry

The hydrochemistry of playas in Western Australia has not received the same scientific attention as salt lakes of south-eastern Australia (see Radke *et al.* 2002, 2003). Surface waters of the Yarra Yarra lakes have been sampled sporadically over the last 20 years (Geddes *et al.* 1981; Brock & Lane 1983; Cruse *et al.* 1989; Regeneration Technology 2001; Smith 2001). They are similar in water chemistry to other Australian inland salt lake systems in that they have alkaline, NaCl dominated brines. Salinity varies greatly between lakes and fluctuates widely in the same lake over time. The pattern of ionic dominance is typical of sea water like the majority of salt lakes in Australia (Drever 1982; Herczeg & Lyons 1991). Ground waters are dominated by NaCl and pH ranges from 3 – 9.8 but is predominantly alkaline near salt lakes.

Methods

As there are in excess of 4, 500 playas in the Yarra Yarra drainage system, a representative six small (< 3 km^2) playas, three pairs of adjacent playas from different sub-catchments, were chosen for study and identified as Mongers A (MONA), Mongers B (MONB), Kadji A (KA), Kadji B (KB) Morawa A (MA) and Morawa B (MB) (Figures 1 and 2). The playas were chosen for their morphological similarity, summarised in Table 1, but each pair were chosen from a different hydrological environment to allow the investigation of hydrology and hydrochemistry across a hydrological continuum.

Catchment analysis

The local sub-catchment of each pair of playas was derived to examine the relationship between catchment characteristics such as size, slope and drainage connectivity to playa hydrology. Five metre contour data made available by the Yarra Yarra Catchment Management Group (Taylor 2001) were used in the ESRI Arc GIS 9.0 software package to generate digital elevation models (DEM) and define connected drainage networks and catchment boundaries for MONA/MONB and MA/MB. The equivalent contour data were not available for the KA/KB catchments, therefore elevation data were derived from the 3 second DEM (Geoscience Australia 2005). Data are regularly gridded at 3 seconds of latitude and longitude (approximately 100 m) from the Shuttle Radar (SRTM).

Surface water measurements

Surface waters were sampled from the middle of each playa and maximum lake depth recorded approximately weekly during wet phases from gauge boards installed in the centre of MONA/MONB (Fig. 2) due to their greater depth, and with a ruler in other lakes. Evaporation rates were calculated from those measurements. All water samples were stored in 500 mL acid washed, plastic bottles in cool conditions prior to analysis. Sample pH and total dissolved solids (TDS) were measured using a TPS® conductivity-TDS-pH-temperature meter in the laboratory. Major cations and anions were measured at the Northern Territory Environmental Laboratories using standard methods: Ca, K, Mg, Na, SO_4 and SiO_2 (ICPOES), PO_4 (FIA), Cl (CL2) and HCO_3 and CO_3 (ALK1). Some samples were diluted to reduce matrix effects due to high TDS.

Table 1

Morphological characteristics of each study playa and piezometer data.

Site	Location (UTM)	Playa Length (m)	Playa Width (m)	Playa Area (ha)	Playa Shape Ratio*	Playa Orientation	Basal Elevation (masl)**	Piezo-meter name	Ground elevation (masl)	Depth (m)	No. of records	Comments
MONA	6731394 E 470977 N	237.6	129.3	2.3	0.52	NW-SE	271.9	A	272.36	1.52	3	
								B	272.345	1.54	3	
								C	272.463	1.28	2	submerged 17/06/03
								D	272.301	1.7	2	submerged 17/06/03
MONB	6730831 E 470970 N	183.1	203.6	2.8	1.0	ESE-WNW	270	A	271.189	1.24	2	
								B	271.203	1.09	2	
								C	271.17	1.09	2	
KA	6769926 E 446696 N	208.3	107.1	2.1	0.65	NNW-SSE	257.2	A	257.831	1.58	6	
								B	257.718	1.64	6	
								C	257.457	0.48	6	
								D	257.668	1.05	6	
								E	257.363	1	5	dry 16/06/03
								F	257.363	1.36	6	
								G	257.428	1.06	6	
								H	257.434	0.99	6	
								I	257.388	0.89	6	
KB	6769720 E 446638 N	148.8	89.3	1.05	0.78	NE-SW	258.9	A	258.87	1.57	3	
								B	258.828	1.93	3	
								C	258.904	1.79	3	
								D	258.901	1.92	3	
MA	6763562 E 403806 N	123.7	99.0	1.15	0.96	NNW-SSE	255.5	A	256.462	1.09	2	
								B	256.477	1.165	2	
								C	256.552	1.235	2	
								D	256.409	1.15	2	
MB	6764320 E 403795 N	167.4	94.4	0.93	0.42	NW-SE	256.8	A	255.294	1.7	3	
								B	255.372	1.68	3	
								C	255.348	1.6	3	
								D	255.245	1.02	3	

* The shape ratio: $S = A / (\pi(L/2)^2)$ compares the area of the shape (A) to the area of a circle with a diameter equal to the length of the longest axis (L) in the shape.

** masl = metres above sea level

Catchment inputs to surface water chemistry were not measured during the monitoring period due to a lack of opportunity to sample the short-lived stream flow events.

Groundwater measurements

Nested sets of piezometers were installed in the basin of each playa (Fig. 2) during dry phases in order to measure horizontal and vertical movement in the hydraulic head of the shallow ground waters. Each nest was surveyed relative to a Western Australian State Survey Mark using electronic surveying equipment to give an elevation relative to sea level. Piezometers were installed to a maximum depth of 2 m, which was deemed sufficient to capture variation in the depth to the water table, and the annulus was sealed with native sediments. Boggy conditions in sites MA and MONB prevented installation until late in the monitoring period and prevented the installation of any piezometers in the middle of MONB. Piezometer data are given in Table 1. Water table levels were measured and waters sampled approximately weekly during wet phases but otherwise irregularly. Groundwater chemistry was analysed following methods outlined for surface water samples. Point water heads were converted to freshwater hydraulic equivalents with a standard freshwater density of 1030 kg/m^3 to make variable densities comparable (Jacobson & Jankowski 1989; Jankowski & Jacobson 1989). Freshwater head equivalents were used in the ESRI Arc GIS 9.0 software package to interpolate hydraulic head contours (potentiometry). Interpolations were calculated within the software based on a nearest neighbour method and made using a regularised spline with an output cell size of 0.5 m. Interpolations and horizontal hydraulic gradient calculations were used to infer the direction of shallow groundwater flow lines. Vertical hydraulic heads were calculated at each piezometer nest and indicated on the potentiometric surface.

The groundwater monitoring regime was biased to wet phase records except in KA, with relatively few measurements due partly to time constraints on the project and conditions unfavourable to the timely installation of some piezometers. The network in MONB was reduced compared to other sites. This has implications for the interpolation of hydraulic head contours, which were based on a nearest neighbours technique and sensitive to the distribution of measured points. Also, while measurements were taken at approximately the same time of day, there may have been several centimetres of diurnal variation that was not measured.

Results

Surface water hydrology

Playas filled for the first time during the monitoring period in March 2003 and were monitored from this time until June 2004. Playa hydroperiods and filling frequencies were highly variable (Fig. 2a–c). In the absence of detailed monitoring and assuming that all water is lost by evaporation, average evaporation rates are given in Table 2 compared with Lake Eyre.

Mongers A and Mongers B

Hydroperiod

MONA had three hydroperiods lasting 44, 84 and 33 days with a maximum depth of 450 mm (Fig. 2a). Monitoring ceased before the end of the fourth hydroperiod that started in early April 2004. MONB held water for the longest period of at least 211 days from early May to early December 2003, reaching a maximum depth of 1000 mm. Monitoring ceased in mid-June 2004 before the end of the second cycle that started in early March 2004. MONA filled from dry to 70 mm depth and MONB increased in depth by 640 mm following 13 mm of rainfall (Fig. 2d) over four days, recorded at the nearby Wanarra station homestead located approximately 5km to the NE during July 2003. Water levels were maintained at 700 – 800 mm for 114 days by numerous small rainfall events of less than 17 mm. A major rainfall event of 80 mm filled MONA and MONB from dry to 160 and 800 mm depth, respectively, during March 2004.

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that MONA and MONB are open basins in terms of surface flow (Fig. 3a). GIS analysis of drainage lines showed that both playas are part of a connected drainage network that empties into Lake Monger, however, the Wanarra road may have

Table 2

Mean evaporation rates and salinity based on weekly lake depth measurements of surface water, and depth and range of shallow groundwater table for each playa. Lake Eyre figures from (Bonython, 1955 and Tetzlaff and Bye, 1978).

Playa	Mean evaporation rate (mm/day)	Mean TDS (g/L)	Mean depth to groundwater (m)**	Groundwater depth range (m)
MONA	5.0	62.6	0.41	0 – 1.44
MONB*	7.8	12.7	0.0	0 – 0.28
KA	0.5	14.15	0.59	0 – 1.15
KB	0.4	34.1	1.05	0.78 – 1.08
MA	6.7	122.5	0.38	0 – 0.66
MB	1.9	185.0	0.36	0 – 1.75
Lake Eyre	4.9–5.8	–	–	–

* not in middle / no dry phase readings

** measurements taken on same dates as groundwater samples (see Table 3)

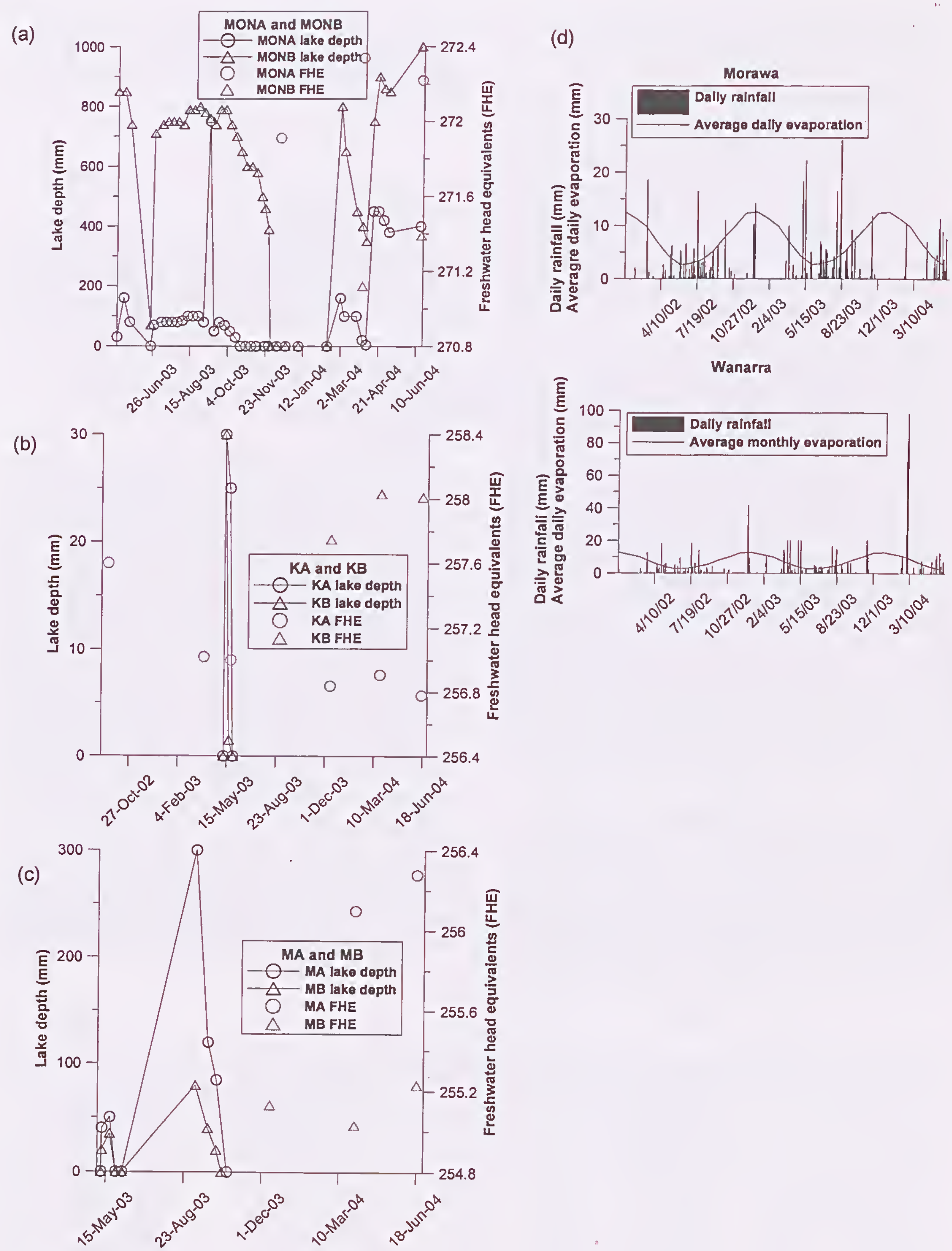

Figure 2. The hydroperiod and average freshwater head equivalents of (a) MONA and MONB; (b) KA and KB; and (c) MA and MB during the monitoring period. Rainfall data from the Morawa townsite records (Bureau of Meteorology, 2004) for Kadji and Morawa sites and from Wanarra landowner records for Mongers sites (d).

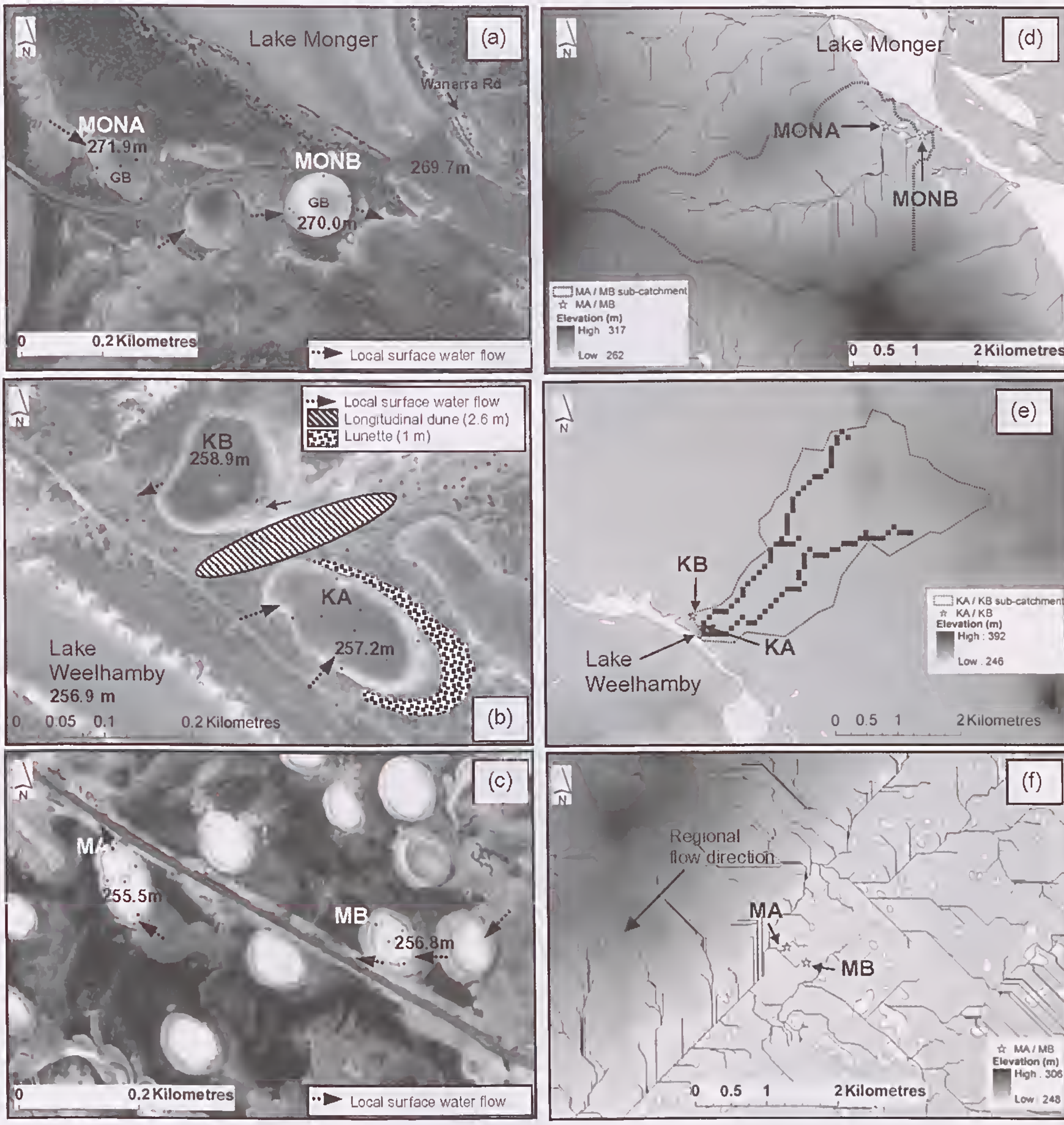

Figure 3. The study playas; (a) Mongers A and B (MONA/MONB), (b) Kadji A and B (KA/KB), and (c) Morawa A and B (MA/MB) showing the location of piezometers and gauge boards (GB), basal elevations and the direction of local surface water flow. GIS derived elevations, sub-catchments and drainage lines of each pair of playas; (d) Mongers, (e) Kadji and (f) Morawa (no catchment defined)

interrupted connection between playas on either side of the road (Figures 3a and 3d). The GIS analysis defined a sub-catchment area of 1043.6 hectares with a mean slope of 1.4% (min: 0%; max: 5.1%; S.D. 0.8%) (Fig. 3d).

Kadji A and Kadji B

Hydroperiod

KA and KB had the shortest hydroperiods, containing 30 mm depth of water or less for a maximum of 19 days during March 2003 following an 18.2 mm rainfall event at Morawa (Fig. 3b).

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that KA and KB are part of separate surface flow networks (Fig. 3b). KA it is a terminal basin for a small local catchment area, separated from the regional surface flows by its bounding dunes. It is bound on the east and south by a 1m high lunette and separated from KB by a 2.6 m high longitudinal dune. It does not have an obvious outflow to the Weelhamby playa but has two small inlets on the west shore, delivering run-off generated from the road (Fig. 3b). In contrast KB is an open basin, connected to the regional

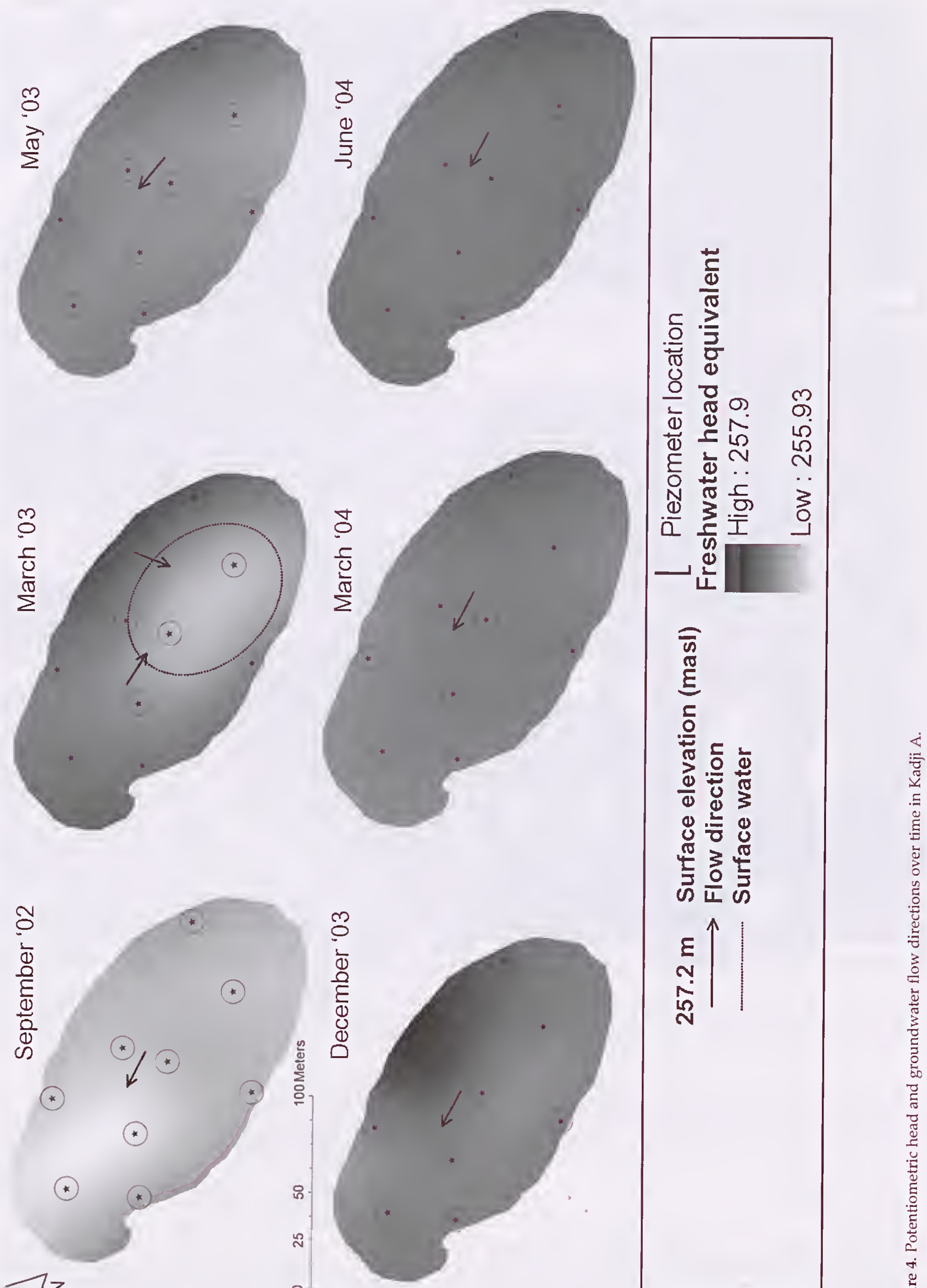

Figure 4. Potentiometric head and groundwater flow directions over time in Kadji A.

drainage which originates in the north-west through an inlet on the east shore with an over-flow to the Weelhamby playa through an outlet on the east shore (Fig. 3b). GIS analysis of the DEM defined a sub-catchment area of 733.86 ha with a mean slope of 1.3% (min 0%; max 6%; S.D. 1.08) (Fig. 3e). The sub-catchment originates at a steep ridge in the east but otherwise has a low slope of < 1.5%. The 3 second DEM generated a connected drainage network which terminated in KA (Fig. 3e). This does not reflect accurately on-ground

Table 3

Ionic composition, salinity and pH of surface water samples.

			Concentration of major ions (g/L)								
Sample #	Lake	Date	Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	alk	TDS	pH
1	KA	10/05/2003	1.7	0.2	0.7	0.1	3.0	1.9	0.1	7.6	7.2
2	KA	20/05/2003	5.2	0.5	1.2	0.3	10.0	3.1	0.0	20.3	8.3
3	KB	10/05/2003	4.9	0.4	0.9	0.3	8.7	2.3	0.1	17.5	7.0
4	KB	20/05/2003	12.8	1.9	1.4	0.5	33.1	5.8	0.2	55.7	7.8
5	MA	10/05/2003	19.0	1.6	1.1	0.6	9.4	4.1	0.1	35.8	7.1
6	MA	20/05/2003	26.6	2.5	1.3	0.7	40.2	6.4	0.0	77.7	8.3
7	MA	28/05/2003	60.2	6.0	1.0	1.5	120.7	11.1	0.1	200.6	8.1
8	MA	7/09/2003	17.3	1.8	0.8	0.4	33.1	4.4	0.1	58.0	7.2
9	MA	23/09/2003	26.8	2.8	1.4	0.7	51.0	7.0	0.1	89.8	7.5
10	MA	4/10/2003	44.3	4.8	1.3	1.2	83.7	9.9	0.2	145.4	7.4
11	MA	17/06/2004	74.0	8.1	0.8	1.8	141.0	15.6	0.1	241.3	7.1
12	MB	10/05/2003	22.1	2.0	1.4	0.6	31.8	5.6	0.1	63.7	6.6
13	MB	20/05/2003	25.1	2.6	1.6	0.7	48.0	7.2	0.1	85.2	7.8
14	MB	7/09/2003	44.2	3.8	1.3	1.3	87.9	8.7	0.1	147.3	7.0
15	MB	23/09/2003	72.0	6.6	0.9	2.0	136.1	12.1	0.2	229.8	7.3
16	MB	4/10/2003	94.9	14.2	0.3	3.9	187.7	23.8	0.3	325.1	7.3
17	MB	17/06/2004	97.0	11.1	0.4	3.0	168.9	18.9	0.1	299.4	6.6
18	MONA	11/05/2003	8.6	0.9	0.8	0.3	15.0	2.4	0.1	28.1	8.6
19	MONA	20/05/2003	6.3	0.6	0.5	0.2	10.8	1.7	0.1	20.3	8.8
20	MONA	27/05/2003	7.9	0.8	0.7	0.3	20.7	2.1	0.1	32.6	8.9
21	MONA	10/06/2003	11.3	1.2	0.9	0.4	15.3	2.8	0.1	31.8	8.8
22	MONA	12/07/2003	17.3	2.0	1.3	0.7	34.6	4.7	0.1	60.6	7.3
23	MONA	26/07/2003	24.7	2.9	1.6	0.9	53.1	6.2	0.1	89.4	7.0
24	MONA	9/08/2003	38.2	4.7	1.6	1.3	76.6	8.2	0.2	130.9	7.0
25	MONA	30/08/2003	19.8	2.4	1.1	0.7	39.9	4.8	0.1	68.7	7.1
26	MONA	7/09/2003	24.4	3.0	1.6	0.8	45.3	6.4	0.2	81.6	7.2
27	MONA	23/09/2003	47.0	6.1	1.3	1.5	90.6	9.1	0.3	155.9	7.1
28	MONA	23/03/2004	7.9	0.9	0.7	0.3	14.7	2.4	0.1	27.1	7.3
29	MONA	31/03/2004	21.6	2.6	1.5	0.9	42.0	5.8	0.1	74.4	7.9
30	MONA	5/04/2004	46.4	6.1	1.5	1.7	91.9	9.2	0.2	156.9	7.4
31	MONA	14/04/2004	0.4	0.0	0.0	0.0	0.9	0.1	0.0	1.5	7.4
32	MONA	21/04/2004	2.2	0.2	0.2	0.1	4.7	0.6	0.1	8.1	7.6
33	MONA	28/04/2004	2.7	0.3	0.2	0.1	5.9	0.7	0.1	10.0	7.5
34	MONA	4/05/2004	3.3	0.4	0.2	0.1	7.6	0.8	0.1	12.6	7.8
35	MONA	16/06/2004	3.9	0.4	0.2	0.2	8.2	0.9	0.1	13.9	9.0
36	MONB	11/05/2003	1.8	0.2	0.1	0.1	3.7	0.5	0.1	6.5	8.1
37	MONB	20/05/2003	1.8	0.2	0.1	0.1	3.8	0.5	0.1	6.7	8.7
38	MONB	27/05/2003	2.0	0.2	0.1	0.1	3.8	0.6	0.1	7.0	9.1
39	MONB	18/06/2003	2.2	0.2	0.1	0.1	3.9	0.6	0.1	7.3	9.7
40	MONB	12/07/2003	2.6	0.3	0.2	0.1	5.4	0.7	0.1	9.2	8.9
41	MONB	26/07/2003	2.8	0.3	0.2	0.1	5.5	0.7	0.1	9.6	9.5
42	MONB	9/08/2003	3.0	0.3	0.2	0.1	5.5	0.7	0.1	9.9	9.3
43	MONB	30/08/2003	3.1	0.3	0.2	0.1	6.3	0.8	0.1	10.9	9.4
44	MONB	7/09/2003	3.3	0.4	0.2	0.1	6.7	0.8	0.1	11.5	9.5
45	MONB	23/09/2003	3.7	0.4	0.2	0.1	7.1	0.9	0.1	12.5	9.7
46	MONB	4/10/2003	4.3	0.5	0.2	0.2	9.0	1.0	0.1	15.3	9.3
47	MONB	19/10/2003	5.3	0.6	0.3	0.2	10.3	1.2	0.1	17.9	8.7
48	MONB	30/11/2003	20.7	2.5	0.8	0.8	42.2	4.6	0.1	71.7	6.8
49	MONB	23/03/2004	2.0	0.2	0.2	0.1	3.4	0.6	0.1	6.6	7.8
50	MONB	31/03/2004	3.1	0.4	0.2	0.1	6.7	0.9	0.1	11.6	7.8
51	MONB	5/04/2004	3.7	0.4	0.3	0.2	7.1	1.1	0.1	12.9	8.3
52	MONB	14/04/2004	1.4	0.2	0.1	0.1	2.9	0.4	0.0	5.1	7.3
53	MONB	21/04/2004	1.9	0.2	0.1	0.1	3.4	0.5	0.1	6.3	8.8
54	MONB	28/04/2004	2.1	0.2	0.1	0.1	3.4	0.5	0.1	6.5	8.9
55	MONB	4/05/2004	2.4	0.3	0.1	0.1	4.8	0.6	0.1	8.3	8.2
56	MONB	16/06/2004	2.3	0.3	0.1	0.1	4.8	0.5	0.1	8.3	9.6

conditions, suggesting that resolution of the DEM was too coarse to detect the local dune topography which appears to be important in directing surface runoff.

Morawa A and Morawa B

Hydroperiod

MA and MB had two complete inundation cycles during 2003, one in May and one in July / August with hydroperiods of less than 45 days with a maximum depth of 300 and 80 mm in each playa respectively (Fig. 2c). The playas held water following a rainfall event of 18.2 mm recorded at Morawa during May, then dried out and re-filled following eight consecutive days of small events (measuring 0.6 – 6.6 mm) totalling 18.8 mm in July 2003.

Catchment analysis

On-ground observations and visual interpretation of the aerial photography show that MA and MB are open basins in terms of surface flow, with one inlet and one outlet (Fig. 3c). GIS analysis of drainage lines show that they are part of a regional drainage system that flows to the south-west. The playa sub-catchments could not be defined using the DEM due to the flat topography thus they are part of the regional catchment for the entire palaeodrainage in this area (Fig. 3f). This makes them different from KA/KB and MONA/MONB which have local sub-catchments and is related to the geomorphological origins of the playas.

Groundwater hydrology

KB had on average the deepest water table while the MONA water table was on average, present at the surface (Table 2). The shallow ground water suggests that the playas are likely to be net discharge points for ground water during dry phases. However, small, local vertical head gradient variations indicate that groundwater is not discharging at the same rate across the playa surface. In all playas, temporary zones of recharge occurred when surface water was present. For example, MONB during the dry period of December '03 was in a discharge phase compared with a recharge phase recorded during the significant wet period in June following year. This shift coincided with a change in flow direction from NW to SE (downstream).

The potentiometry of KA derived from the GIS interpolation is given as an example in Figure 4, with general directions of shallow groundwater flow and vertical hydraulic gradients indicated. The water table is horizontal and horizontal hydraulic gradients are small, for example ranging from 0.002 – 0.0002 in March '03. However, the lateral and vertical direction of local, shallow groundwater flow is not temporally consistent. For example, lateral flow in September '02 was towards the NW (downstream). At this time the lake was primarily in a discharge phase, compared to the following year in March during a minor wet phase when flow into central recharge zone.

Hydrochemistry

pH and TDS

Surface waters varied more widely in pH (6.6 – 8.9) and TDS (1.5 – 325 g/L) (Table 3) than groundwater samples. Ground waters (Table 4) had a small pH range of 6.5 – 7.5. TDS ranged between 118 – 326 g/L except in three samples (12–14) where TDS was < 77 g/L.

pH decreased with increasing salinity in both ground and surface waters. pH increased with maximum depth in surface waters while TDS decreased with maximum depth (Fig. 5). MONB consistently had the lowest salinity and highest pH throughout the monitoring period due to its relatively deep surface water.

Table 4

Ionic composition, salinity, density and pH of ground water samples.

Sample #	Lake	Date	Concentration of major ions (g/L)									
			Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	alk	TDS	Density (kg/m^3)	pH
1	KA	10/05/2003	69.5	8.8	0.8	2.5	117.6	14.1	0.1	213.3	1169.0	6.8
2	KA	20/05/2003	68.5	8.6	0.8	2.4	123.0	14.2	0.1	217.5	1172.6	7.0
3	KA	28/05/2003	68.5	8.6	0.8	2.4	127.2	14.1	0.1	221.6	1176.3	7.0
4	KA	12/12/2003	69.8	9.0	0.7	2.4	131.7	17.5	0.1	231.2	1184.7	6.9
5	KA	23/03/2004	72.2	9.1	0.7	2.5	147.3	17.6	0.1	249.6	1201.2	7.0
6	KA	16/06/2004	66.6	8.9	0.8	2.3	129.2	17.0	0.1	224.8	1179.0	7.0
7	KB	12/12/2003	75.0	10.7	0.6	2.9	145.2	19.1	0.1	253.6	1204.8	6.6
8	KB	23/03/2004	74.4	10.9	0.6	3.0	144.7	20.2	0.1	253.8	1205.0	6.9
9	KB	16/06/2004	74.4	10.8	0.5	2.9	146.4	19.7	0.1	254.7	1205.9	6.8
10	MA	30/03/2004	84.1	9.5	0.6	1.9	154.8	17.1	0.1	268.0	1218.0	6.7
11	MA	17/06/2004	48.1	4.8	1.0	1.2	91.9	10.0	0.1	157.1	1121.0	7.0
12	MB	12/12/2003	90.4	13.1	0.4	3.1	177.9	22.1	0.4	307.4	1254.7	6.8
13	MB	23/03/2004	35.0	4.8	0.6	1.1	69.0	7.7	0.1	118.2	1089.0	7.0
14	MB	30/03/2004	94.9	14.5	0.3	3.6	186.3	25.2	0.3	325.1	1271.6	7.0
15	MB	17/06/2004	94.5	6.6	0.7	2.3	177.5	12.3	0.2	294.1	1242.1	6.7
16	MONA	12/12/2003	61.6	9.0	0.7	1.9	118.7	13.1	0.1	205.0	1161.7	6.5
17	MONA	31/03/2004	41.6	5.6	0.7	1.3	79.7	8.8	0.1	137.7	1104.9	6.9
18	MONA	16/06/2004	22.7	2.5	0.6	0.9	45.9	4.2	0.1	76.8	1056.1	7.5
19	MONB	31/03/2004	19.6	2.0	0.5	0.8	40.1	3.7	0.2	66.8	1048.3	6.9
20	MONB	16/06/2004	8.5	1.0	0.3	0.3	17.4	1.6	0.1	29.2	1019.6	6.6

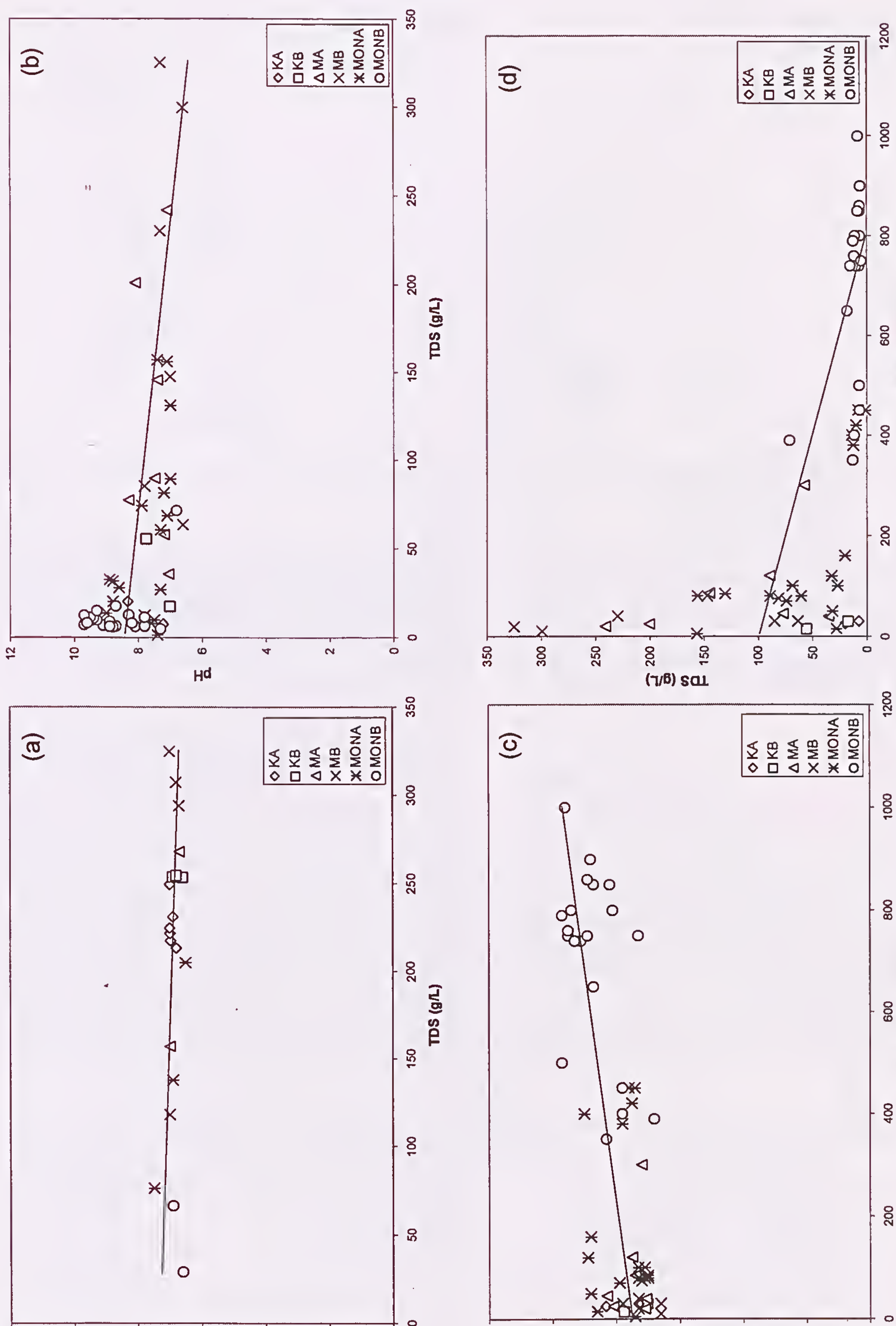

Figure 5. The relationship between pH and TDS in (a) groundwater, (b) surface waters and pH and TDS relationships to surface water depth (c & d respectively).

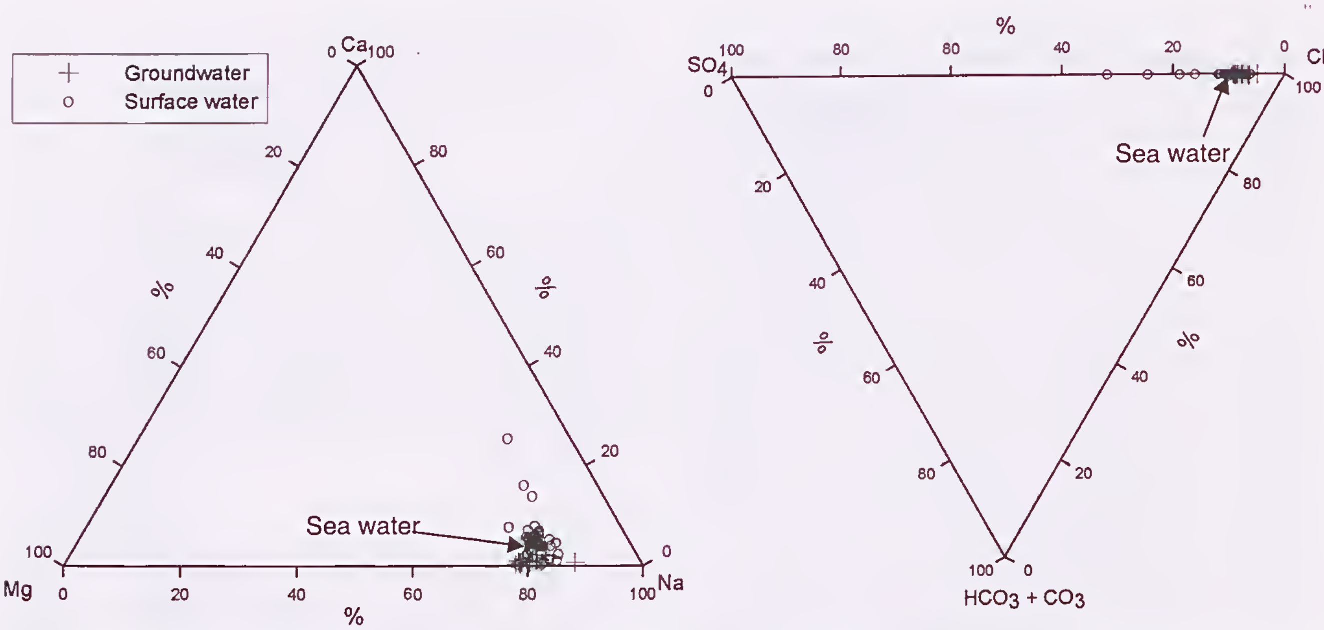

Figure 6. Ternary diagrams showing the relative proportion on ions in surface water and groundwater samples compared to sea water.

Eight ground water and surface water samples were taken synchronously. Surface samples were less saline than corresponding ground waters except in MA and MB. The correlation value between the TDS of the two waters was 0.33, however, it increased to 0.84 with the exclusion of samples from KA (10/05/03; 20/05/03), which had the greatest gradient of TDS between surface and ground waters.

Ionic analyses

Ionic analysis of the ground water samples showed a consistent pattern of ionic dominance: $Na^+ > Mg^{2+} > K^+ > Ca^{2+}$: $Cl^- > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$ (Table 5). Using the Eugster & Hardie (1978) method of nomenclature for comparing brine types, the ground waters are type Na-(Mg)-Cl-(SO4) (Table 5). The relative proportions of major solutes in groundwater samples did not vary remarkably between playas as shown in the ternary plots (Fig. 6). The plots are consistent with saline ground waters elsewhere in Western Australia which are dominated by Na and Cl ions.

Similarly, playa surface waters were dominated by Na and Cl (Fig. 6); however, they showed a slightly more varied ionic dominance than the groundwater samples. The majority of samples had a pattern of ionic dominance consistent with that typical of sea water: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$: $Cl^- > SO_4^{2-} > HCO^{3-} > CO_3^{2-}$ (Table 5). However seven samples deviated from this pattern being either enriched (samples 1, 2, 9) or comparatively depleted in Ca^{2+} (samples 53–56) to resemble ground waters (Table 5).

The relationships between ionic ratios and salinity in all water samples are shown in Figure 7. They are similar to those described by Jankowski and Jacobson (1989) who investigated the evolution of regional fresh groundwater inflow to saline ground water brines in playas of central Australia. We propose that shallow ground water brines sampled in this study have evolved *via* a geochemical pathway similar to the 1B pathway described by Jankowski and Jacobson (1989). The pathway is illustrated in Figure 8 and related to playa physical hydrology. The three phases of a hydroperiod, namely flooding, evaporative concentration and desiccation are accompanied by three brine types of varying composition: the initial composition, in this case the composition of rainwater in the vicinity of the Yarra Yarra drainage system after Hingston & Gailitis (1976);

Table 5

Brine classification of surface waters and ground waters (parentheses) compared to sea water.

Pattern of ionic dominance	Sample (refer Table 3 and 4))
Na>Ca>Mg>K : $Cl>SO_4>HCO_3>CO_3$	1,2,9
Na>Mg>Ca>K : $Cl>SO_4>HCO_3>CO_3$	3-8, 10-52; seawater
Na>Mg>K>Ca : $Cl>SO_4>HCO_3>CO_3$	53-56; (1-20)
Eugster and Hardie	
Na-(Ca)-(Mg)-Cl-SO_4	1
Na-(Ca)-(Mg)-Cl-(SO_4)	2,9
Na-(Mg)-(Ca)-Cl-(SO_4)	3-8, 10-15, 17-19, 22, 24 26-39, 41-50; seawater
Na-(Mg)-Cl-(SO_4)	16, 20, 21, 23, 25, 37-40, 51-56; (1-20)

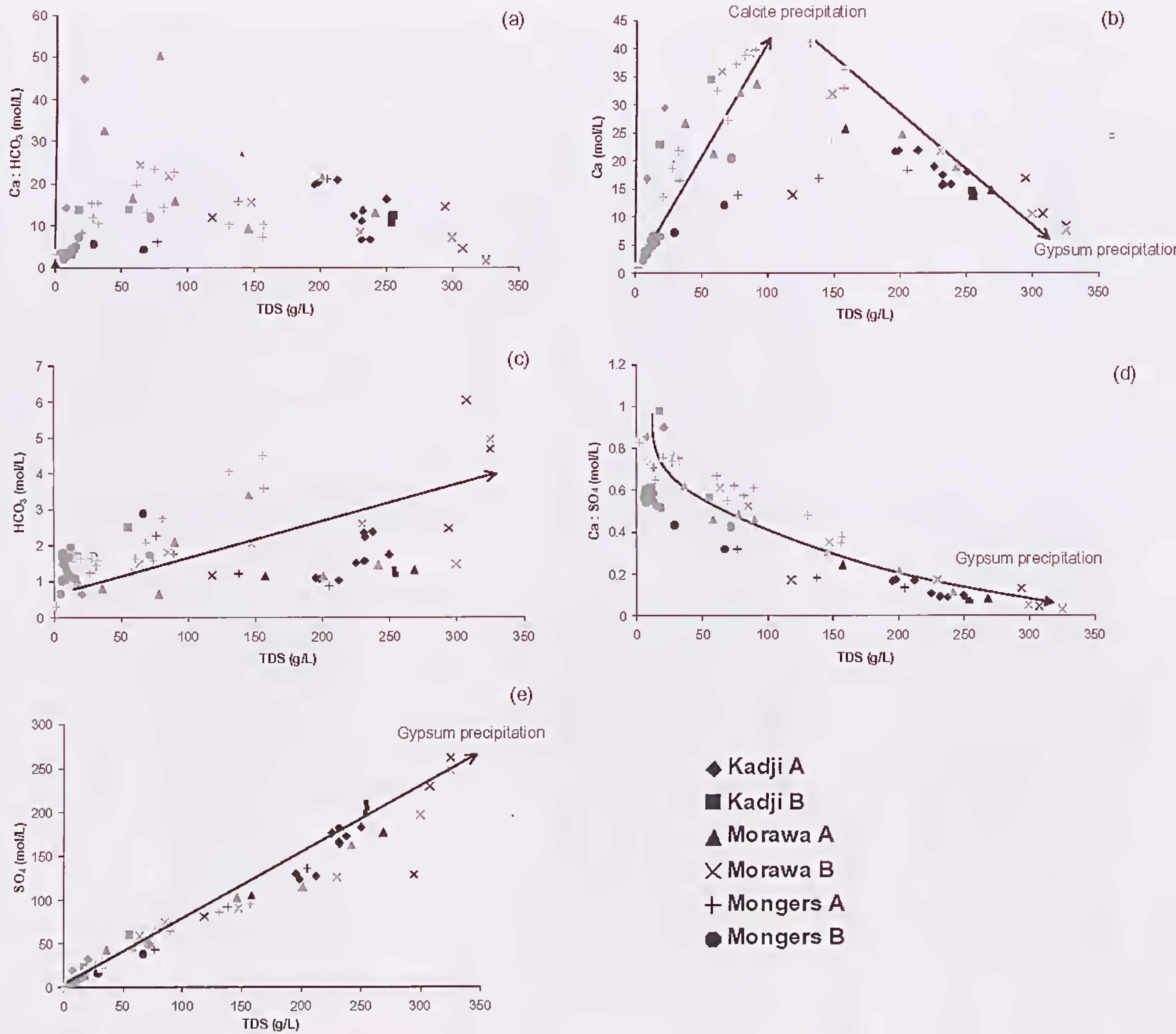

Figure 7. (a) Ca: HCO_3 ratio and (b) Ca and (c) HCO_3 concentration relationship to salinity in ground waters (black symbols) and surface waters (grey symbols); (d) Ca: SO_4 ratio and (e) SO_4 concentration relationship to salinity in ground waters (black symbols) and surface waters (grey symbols). Arrows identify the direction of mineral precipitation.

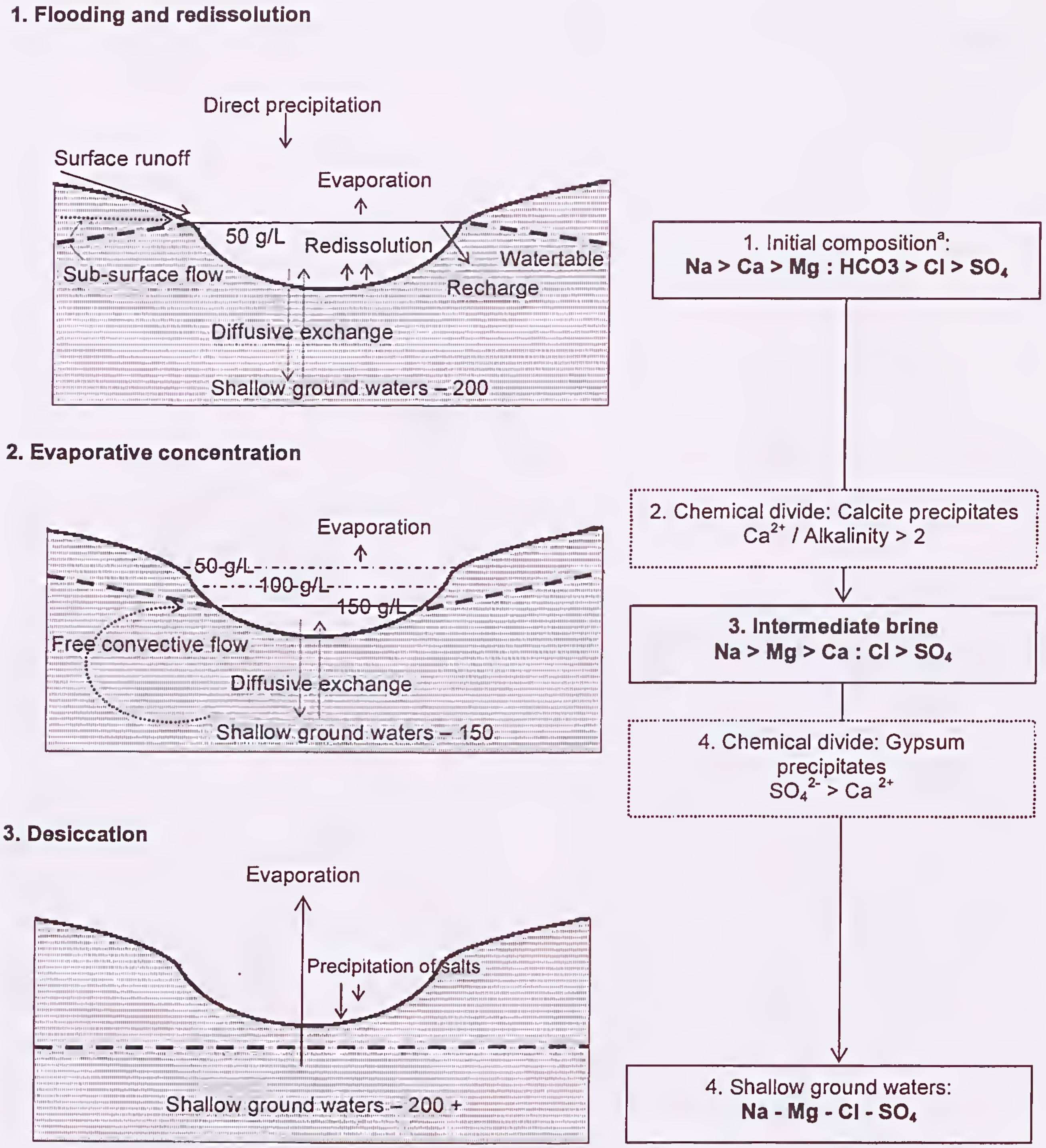

Figure 8. Potential pathway for brine evolution based on 1B pathway of Jankowski and Jacobson (1989), in relation to the physical hydrology of the playas modified from Shaw & Thomas (1989) and Fan *et al.*, 1997. [a] Initial composition derived from Hingston & Gailitis (1976).

the intermediate brine that persists after the first chemical divide where calcite precipitates; and the resulting shallow groundwater brine that evolves after the second chemical divide where gypsum precipitates.

Discussion

As ephemeral lakes, the playas studied here display a combination of characteristics and processes common to both permanent and permanently dry lake types. We discuss the results of the research in three parts: factors influencing the mechanics of surface water hydrology; the hydrology of shallow groundwater; and processes defining the hydrochemical character of the playas.

Surface water hydrology

The playas represent a combination of stages C and D in Bowler's (1986) continuum of lake basins. During the

monitoring period, the continuum was exemplified through MONB at the 'C end' (most often wet) and KA at the 'D end' (most often dry). Collectively they are ephemeral basins and therefore alternate between two distinct hydrological phases; *the wet phase* of variable length and salinity, comprised of three internal hydrochemical phases of i. inundation, ii. evaporation and iii. desiccation; and *the dry phase* consisting of variable drought periods in which playas are primarily groundwater-dominated or discharge playas (Fig. 8). Geomorphically the 6 playas are similar in that they are elliptical to circular and shallow (< 1 m). According to Bowler's continuum, KA should have an irregular outline if it is a true groundwater dominated playa, however its smooth shorelines may be an inherited feature from past high rainfall periods. Thus the morphology of the lake is not necessarily reflecting the current hydrologic environment.

The frequency and duration of filling events in playas of the Yarra Yarra system is controlled in part by rainfall distribution across the catchment reflecting rainfall patchiness and variable catchment characteristics. The progressive SW to NE pattern of decreasing average rainfall is likely to produce variable spatial and temporal patterns in playa filling frequency and hydroperiod, although this has not been investigated systematically and remains the subject of further work in the catchment. In addition, the downstream topographic gradient along the drainage line is variable. Low gradient stretches in the system, for example the southern section of Lake Monger and the 40 km stretch south of Lake Nullewa (see Fig. 6 Boggs *et al.* 2006), may act as surface water sinks further influencing the distribution and residence time of surface water.

Detailed analysis of filling frequency and hydroperiod using remotely sensed data has been performed on other Australian salt lake systems (Turner *et al.* 1996; Roshier *et al.* 2001). Roshier *et al.* (2001) identified that three successive months of 20 mm rainfall was a sufficient threshold for filling playas in arid Australia. We identified that an event or a series of events totalling 18.8 mm triggered a filling event in all playas investigated. However, such events did not *always* result in a filling event in all lakes, suggesting that factors other than rainfall, *e.g.* drainage connectivity, contribute to playas filling. For example, MA/MB and MONA/MONB are located in similar average rainfall zones (Fig. 1) but had very different filling regimes. This could be attributed mostly to the variability in rainfall between the two sites during the monitoring period (Fig. 3c), however they also have markedly different catchment characteristics. The sub-catchment derived for MONA/MONB appears to be effective in generating run-off, *i.e.* high slope with strongly connected drainage channelling creek water directly into the playas. In comparison, MA/MB are part of a very flat, large regional catchment with comparatively poorly connected drainage network. For KA/KB the rainfall record taken at Morawa may be too far away to reflect accurately the rainfall in the sub-catchment. Being in a low rainfall zone, it was not unexpected that KA/KB had very little surface water during the monitoring period. KA, in particular, rarely is likely to accumulate appreciable surface water given that it is separated from the sub-catchment drainage by dunes.

In all playas, the pre-condition of the catchment will play a significant role in the amount of run-off and/or subsurface flow that enters the basin. Factors including the soil saturation and resultant runoff and/or seepage from the capillary fringe as well as the catchments efficiency in delivering run-off to the playas will contribute to the amount of water entering the basin.

The evaporation rates for each lake do not necessarily reflect the inverse relationship between evaporation rate and surface water salinity that is often recorded in saline water bodies (Drever 1982; Kotwicki 1986; Yechieli & Wood 2002). The evaporation rates recorded vary widely, suggesting that loss is occurring through avenues other than direct evaporation. For example, the rates for MONA/MONB are likely to be high; the playas undoubtedly lost surface water downstream to the Mongers playa through the surface water outlet (Fig. 2c).

Groundwater hydrology

Regional groundwater flow in the Yarra Yarra drainage system is towards the playas, which are topographical low points, and inferred local discharge points for groundwater (Commander & McGowan 1991). Therefore, simplistically, regional recharge flows into the playas and leaves *via* evaporation from the playa floors. However, we have presented some evidence here of more variable patterns of local groundwater movement that respond to the presence of surface water. The playas probably recharge to the unsaturated zone between the lake bed and the water table during wet phases. Unlike some playa systems further inland, such as those in the Eastern Goldfields of Western Australia, the Yarra Yarra lakes receive relatively regular runoff and are therefore likely to recharge annually through their basin floors or through permeable basin margins. Recharge may also be occurring outside the basins in porous dune areas and adjacent calcrete deposits (Commander & McGowan 1991) and enter the playas as relatively fresh sub-surface flow.

The playas are not likely to be hydrologically closed but through-flow playas and part of a regional groundwater flow system supported by the consistent chemistry of their local groundwater. Given that regional lateral groundwater flow is catchment controlled, then movement will be very slow as the average topographic gradient along the lowest part of the salt lake valley between Lake Monger and Yarra Yarra is less than 0.0005% or a total decline of only 52 m over 270 km (Boggs *et al.* 2006).

Variations in the position of the water table relative to the elevation of the basin may be significant to the hydrochemistry of the playas through the relative contribution of recharge waters (Shaw & Thomas 1989) and the preservation of salts, *i.e.* the development of evaporative crusts. Jacobson and Jankowski (1989) in their investigation of central Australian playas found that adjacent playas at different elevations (*e.g.* Glauberite Lake compared to more elevated Lake Amadeus) are differentially affected by groundwater. The 6 playas investigated here have variable elevations and positions in the landscape relative to other playas that might influence their hydrological characteristics (see Fig. 2). KA/KB and MONA/MONB have evolved peripherally to large adjacent playas (Weelhamby and Mongers

respectively) while MA/MB are located within the main palaeodrainage and probably segmented remnants of a larger playa in this area. Here the playas are known to develop thick evaporative crusts, this combined with the flat topography and poorly connected surface drainage suggests that playas are likely to be strongly influenced by shallow ground waters. The similarity of surface water and groundwater salinity in MA/MB supports this proposition.

Hydrochemistry

The small playas investigated did not show any unique chemical characteristics during the monitoring period but were consistent with previous hydrochemical research undertaken on playas in Yarra Yarra catchment (Geddes *et al.* 1981; Brock & Lane 1983; Cruse *et al.* 1989; Regeneration Technology 2001; Smith 2001) and with the major reviews of Australian salt lake chemistry (Williams 1967; Buckney 1980; Geddes *et al.* 1981; DeDeckker 1983). The results therefore supported the theory that playa salts are derived from marine aerosols (Chivas *et al.* 1991).

We were able to identify the progressive evaporative concentration of salts (stage 2, Fig. 8) in the water depth to salinity relationship. pH values showed a weak inverse relationship to salinity and therefore water depth, however, the relatively circum neutral pH of both ground waters and surface waters reflects the buffering capacity of Na and Cl as described by Gasse (1986).

Except in MA and MB, the ground waters were less saline than surface waters, indicating that evaporation was proceeding more slowly than diffusive exchange; thus, with progressive evaporation, diffusive flux between the surface and shallow ground waters progressively reduced the concentration gradient between the waters so that they became chemically more similar with time until the playas dried. Long periods of dry such as in KA will produce highly evolved shallow ground waters, *i.e.* strongly dominated by Na and Cl. In contrast, long periods of wet such as in MONA, halt brine evolution (Yechieli & Wood 2002) thus we might expect the shallow ground waters of playas of the Yarra Yarra catchment to show spatial variability roughly related to the SE-NW rainfall gradient. Low groundwater salinities seen in samples 12–14 possibly represent the diffusive flux (recharge) of low salinity surface waters into the shallow groundwater, presumably with the equivalent upward flux of salts.

Based on the ionic ratios given in Figure 7, it is possible to predict the pathway of shallow groundwater evolution and relate this to the physical hydrology of the playas (Fig. 8). We propose that the shallow ground waters have evolved along the pathway described in Figure 8, *i.e.* pathway 1B, modified from Jankowski and Jacobson (1989). Here, recharge waters have evolved from a low salinity composition, in our case a likely combination of rainwater and regional groundwater, into Na-(Mg)-Cl(SO4) type brines with depleted Ca and HCO_3. Chemical analysis of local rain waters and regional ground waters was not undertaken in this study but would be necessary to confirm conclusively the source and composition of input waters. Nonetheless, the IB pathway requires that the initial waters have a ratio of Ca : HCO_3 of > 0.5 and SO_4 : Ca of > 1 which is common to percolated rainwater containing dilute sea-salts (Yechieli & Wood 2002).

Free convective flow (Fan *et al.* 1997; Yechieli & Wood 2002) is likely to contribute to brine evolution in these playas. The playas satisfy the necessary conditions for free convection to occur. According to Fan *et al.*, (1997) these include a shallow water table and resultant 'wet' playa surface and abundant recharge through regional groundwater flow.

Variations seen in the relative proportions of ions in the surface water could be attributed to capturing different phases in the geochemical pathway during evaporative concentration. We identified from ionic ratios that the playas monitored probably followed the 1B geochemical pathway of Jankowski and Jacobson (1989) where, at the first chemical divide (the initial precipitation of calcite), the calcium to alkalinity ratio is < 2 resulting in waters dominated by Na and Cl with appreciable Mg, Ca and SO_4 as seen in samples 1, 2 and 9 (Table 5). At the next chemical divide, gypsum precipitates and if the SO_4 concentration then remains greater than Ca concentration, we derive a Na and Cl dominated brine with appreciable SO_4 and Mg. Therefore, the ground waters chemically appear to be the concentrated end product of evaporated surface waters with reduced Ca possibly due to cation exchange (clay adsorption) during infiltration (Herczeg & Lyons 1991). Similar processes have been documented in other lakes in Australia including Lake Eyre and Lake Tyrell (Jankowski & Jacobson 1989).

Despite the relatively consistent water chemistry observed, discrete variations in ionic composition may prove to be significant to playa biology. For example, the species composition of diatom communities is known to be sensitive to anion concentrations, the effects of which may be concentrated by nutrient availability (Servant-Vildary & Roux 1990; Saros & Fritz 2000a, b). Therefore in addition, catchment inputs should be quantified. This could be particularly important in the Yarra Yarra catchment which is dominated by agricultural landuses, including the widespread application of super-phosphate fertilisers and gypsum soil improvers (Boggs *et al.* in press).

Conclusions

The hydrology of six small playas in the Yarra Yarra drainage system of Western Australia was monitored over two wet seasons. The six playas represent a hydrological continuum of ephemeral basins from mostly wet to mostly dry. The variability seen in hydroperiod and filling frequency was largely dependent on rainfall variability, sub-catchment size and slope and local drainage connectivity.

Ground waters were generally less than 1 m below the playa surface and essentially flat under each playa reflecting the low topographic gradient. While likely to be net discharge playas, there were spatial and temporal variations in hydraulic head indicating that local, shallow groundwater movement is complicated by the presence of surface water and the playas may switch to a recharge mode for short intervals. More widespread investigations of groundwater movement facilitated by

a longer monitoring period and more comprehensive piezometer networks as well as measurements of diurnal variations in the watertable are needed to determine the sub-surface flow inputs which would help complete the understanding of hydrochemistry of the playas.

Hydrochemically, the playas were not unlike other playas in Australia. They display a wide range of salinity, neutral to alkaline pH and ionic composition similar to seawater. We postulate that the geochemical evolution of waters in the playas follows the 1B pathway of Jankowski and Jacobson where low salinity recharge waters with seawater salts progress to Na-Cl dominated brines through evaporative concentration. The similarity of groundwater and surface water TDS suggest there is interchange occurring between the two waters.

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An endangered species that is also a pest: a case study of Baudin's Cockatoo *Calyptorhynchus baudinii* and the pome fruit industry in south-west Western Australia

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Abstract

Baudin's Cockatoo *Calyptorhynchus baudinii* is an endangered species that is endemic to south-west Western Australia. It is also a declared pest of agriculture because it damages apple and pear (pome fruit) crops in commercial orchards. Although it is unlawful, some fruit growers shoot and kill the cockatoos to prevent fruit damage. A survey of pome fruit growers during the 2004/2005 season showed that shooting to kill can-not be justified in terms of the damage the cockatoos cause or the costs of damage control incurred by growers. Estimated loss of income to fruit damage by birds equated to 6% of farmgate income and the cost of damage control represented 2% of farmgate income. Damage levels varied significantly between individual properties and pink lady apple was the most commonly and severely damaged fruit variety. This study has shown that non-lethal scaring techniques are effective for protecting pome fruit from damage by Baudin's Cockatoo.

Keywords: Baudin's Cockatoo, *Calyptorhynchus baudinii*, pome fruit industry, Western Australia

Introduction

Baudin's Cockatoo (*Calyptorhynchus baudinii*), the long-billed White-tailed Black Cockatoo, has been known to damage fruit in apple and pear (pome fruit) orchards since the early 1900s (Halse 1986). In the past, the damage was managed by a number of lethal means via notices published in the Western Australian Government Gazette (Table 1). These means included government bonus payments for the destruction of the cockatoos and open seasons for shooting, in selected shires, when causing damage to fruit (Table 1).

This cockatoo, which is endemic to the south-west of Western Australia, may no longer be killed to protect fruit crops, because it has been listed as a threatened species since 1996. Using IUCN (1994) Red List Categories and Criteria, Baudin's Cockatoo is listed as Endangered in Western Australia and Vulnerable Nationally. Illegal killing of these cockatoos continues (CALM 2005) and, along with habitat loss and competition for nest hollows with feral honeybees, illegal shooting to protect pome fruit crops is one of the principal threats to the population (CALM 2006).

Presumably, those fruit growers who shoot the cockatoos do so because they believe: the cockatoos are the principal pest of pome fruit crops; the damage the cockatoos cause results in significant loss of income; the cost of non-lethal crop protection is excessive; and non-lethal techniques, such as scaring, are not effective or not cost effective. The purpose of this study was to assess the validity of these perceptions via a grower survey.

A grower survey was conducted during and after the 2004/2005 pome fruit season. The purpose of the survey was to assess the attitudes of the growers toward the conservation status of the cockatoo and to assess the cost of damage and damage control to growers. Data on the damage control methods employed by growers were collected to assess the effectiveness of the non-lethal techniques employed.

The limitations of grower surveys versus quantitative measurements have been discussed elsewhere (*e.g.* see Bomford and Sinclair 2002) and so will not be discussed in detail in this paper. Although grower surveys may be limited by the skill, honesty and motivation of the participants, they do provide an overview and would be expected to represent the experiences of the growers across the industry.

Materials and Methods

A survey of fruit production, fruit damage and damage control efforts was prepared by the author, based on other studies of bird damage (*e.g.* Lim *et al.* 1993), and in consultation with the Executive Manager of the Western Australian Fruit Growers' Association (WAFGA). The survey was posted to all 277 fruit growers registered as apple and pear growers with WAFGA in May 2005. The survey was confidential, but respondents were asked to provide contact details to clarify the data provided. The growers were provided with a reply paid envelope to encourage them to return the surveys and members of the Warren Catchments Council assisted by collecting surveys in person. A space allowing growers to make written comments was provided at the end of the survey.

Table 1

Summary of changes to the pest and conservation status of Baudin's Cockatoo in Western Australia over time.

Time period	Pest and conservation status	Reference
1950s and 1960s	Bonuses or bounties paid by Bridgetown Shire.	Whittell (1950) and Saunders (1974)
1978	May be taken when causing damage to fruit.	WA Govt Gazette, June 16, 1978
1980	Numbers to be controlled and/or reduced in the Shires of Denmark, Donnybrook and Plantagenet	WA Govt. Gazette, 12 December 1980
1988	A management program outlines the conditions under which controls for Baudin's Cockatoo be applied	WA Govt. Gazette, 09 December 1988
1989 to present	Killing of Baudin's Cockatoo to protect fruit crops (or for any reason) is an offence under the provisions of the Western Australian *Wildlife Conservation Act 1950.*	WA Govt Gazette, 19 May 1989
1996 to present	Listed as a threatened species (Endangered using IUCN (1994) Red List Categories and Criteria), under the provisions of the Western Australian *Wildlife Conservation Act 1950.*	WA Govt Gazette, 30 April 1996

The survey asked growers if they knew Baudin's Cockatoo is endangered and if they thought it should be protected, even though it damages fruit crops. They then listed their top five bird pests in the order of the damage they cause, from 1–5 most to least damage. The survey asked if growers had ever had a problem with Baudin's Cockatoo damaging their fruit crop and if Baudin's Cockatoo had damaged their crop in the last 12 months. The monetary cost of damage to the fruit by birds during the 2004/2005 season (in terms of loss of farmgate income) was estimated by growers.

A table was provided for growers to fill in their crop type(s) (apple or pear), variety of fruit and the area of planting (ha) and the number of trees for each variety. The months in which damage occurred was recorded and the extent of the damage was ranked from (1): None to (6): Extreme against each variety. The categories of damage were modelled on those used by Lim *et al.* (1993) and modified in consultation with WAFGA, based on the percentage of fruit lost.

The survey asked growers if they had previously used pest control to stop Baudin's Cockatoo damaging their crop. If they had previously used pest control, growers filled in a table of the number of days and hours per day damage control was undertaken during the 2004/2005 season and the cost of damage control per hour (including wages and consumables). These data were used to calculate the total cost of damage control for the 2004/2005 season.

A table of commonly used damage control techniques was provided and growers were asked to rate the effectiveness of the techniques from (a): Not effective to (e): Highly effective, against each of the techniques they used to protect crops from damage by Baudin's Cockatoo. For those growers who had used a combination of damage control techniques, the effectiveness of these was categorised into the same ratings of effectiveness. Space was made available for growers to list and rate 'other' damage control techniques that were not shown on the survey.

The damage caused by various pest bird species, severity of damage to each fruit variety and the effectiveness of damage control techniques (as shown in the figures) were ranked from highest to lowest using the following weighted calculation (after Lim *et al.* 1993):

$$\text{Index} = \sum \frac{(n_1 \times 1) + (n_2 \times 2) + (n_3 \times 3) \ldots\ldots\ldots (n_6 \times 6)}{n_t} \times \frac{100}{C}$$

Where $n_{1\text{-}6}$ = number of responses for each category, n_t = total number of responses and C = highest category assessed.

All statistical analyses were carried out using JMPIN software (SAS Institute 1996) in accordance with the software instructions (Sall & Lehmann 1996). An ANOVA model was used to examine the relationship between the proportion of fruit damaged and individual properties, shire in which the property was located, crop variety, plantation area, number of trees in the plantation and tree density. Each property was treated as a sampling unit, and property was nested in Shire to prevent repeated analyses of the same data. The data met the assumptions of the test and so did not require transformation. A *post-hoc* Dunnett's Tests ($p < 0.05$) was used to group apple varieties on the basis of proportion of fruit damaged (Sall & Lehmann 1996). Only the three most commonly grown varieties were used in the analysis due to lack of data for the remaining varieties.

Results

Of the 277 surveys that were posted to fruit growers registered as apple and pear growers with the WAFGA in May 2005, 86 (31%) were returned. Five further surveys were returned unopened because the growers either no longer resided on the property or had removed all their pome fruit trees. Since not all survey participants responded to all questions in the survey, the number of responses to each question is shown in the parentheses, after the percentage values, in the text below. Also shown is the sampling error for each response (confidence interval 95%).

The top ranked pest bird species of apple and pear crops were Baudin's Cockatoo, the Australian Ringneck (*Platycercus zonarius semitorquatus*) and the Red-capped Parrot (*Platycercus spurius*) (Figure 1). The majority of growers (72% ± 7.9%, $n = 86$) said they knew

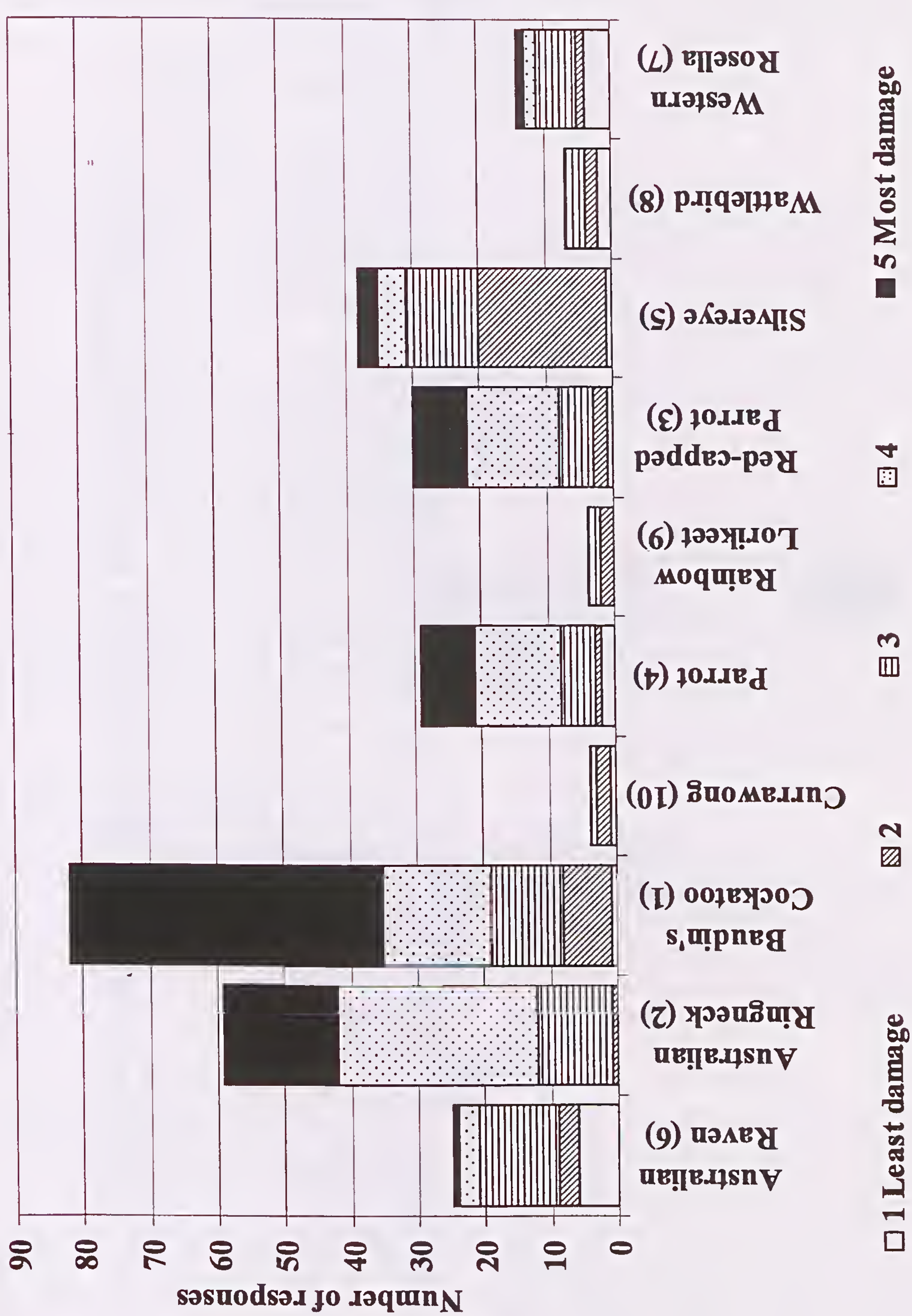

Figure 1. Pest birds of pome fruit crops in south-west Western Australia (n = 292). Values in parentheses show ranking by relative extent of the damage.

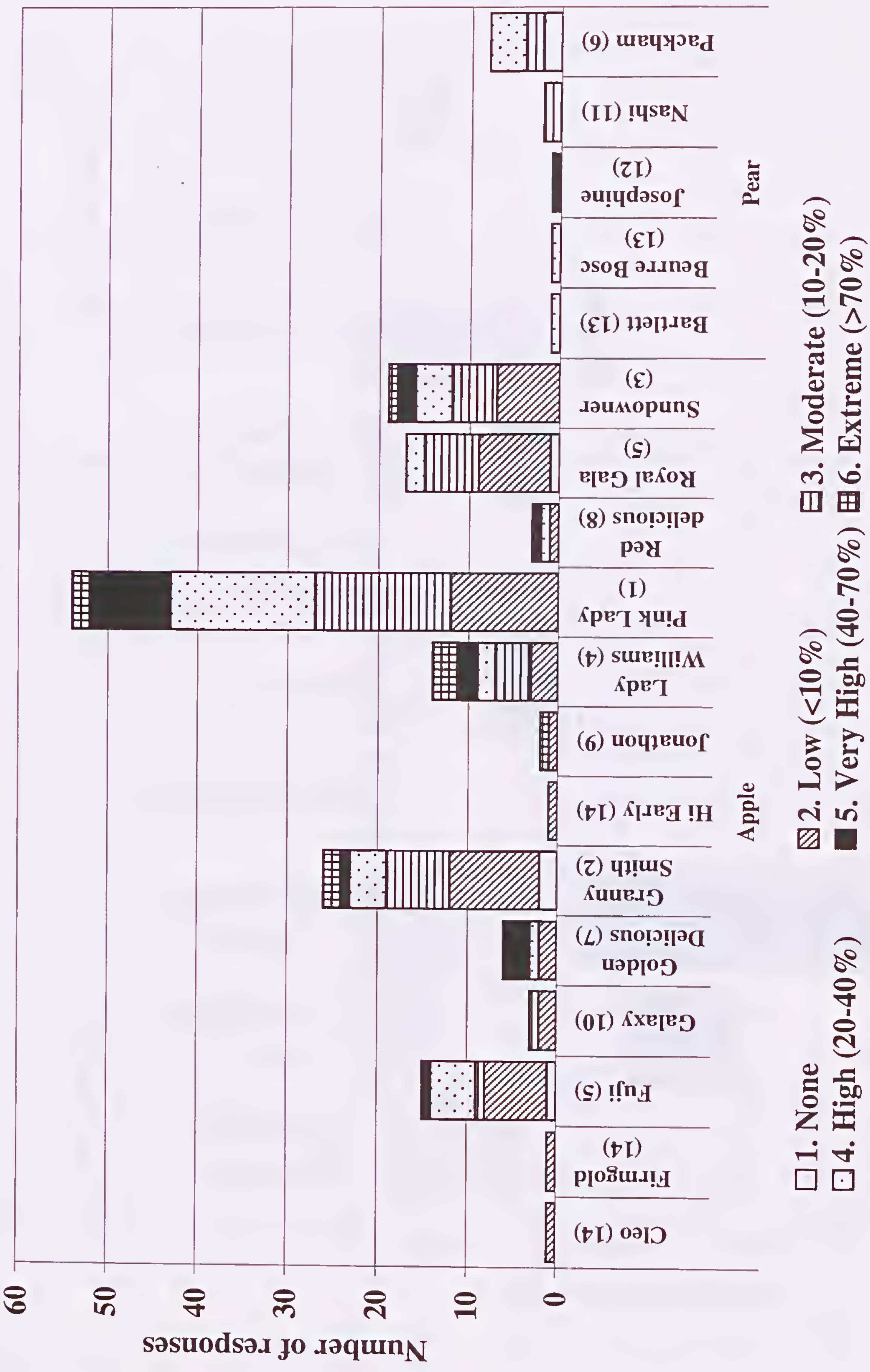

Figure 2. Proportion of fruit damaged by birds for apple and pear crops ($n = 175$). Values in parentheses show ranking for fruit variety by relative extent of damage.

Table 2

Pome fruit orchard parameters and estimate of loss of farmgate income by growers.

	Range	Mean ± s.e.	S.D.	Median	*n*
Orchard size (ha)	0.4 – 50	6.8 ± 1.2	3.8	1	55
Trees per property	9 – 50,000	4,446 ± 977	3,311	500	58
Estimated loss ($)	0 – 150,000	12,453 ± 3,537	25,749	3,000	53

Baudin's Cockatoo was an endangered species in Western Australia and 42% ± 9.1% (*n* = 81) agreed that it should be protected, even though it damages pome fruit. Most of the growers (94% ± 4.2%, *n* = 86) had previously incurred fruit damage by Baudin's Cockatoo and 89% ± 5.6% (*n* = 83) reported that Baudin's Cockatoo had damaged their crop in the previous 12 months.

Fruit value and loss of income

The farmgate value of the fruit in the pome fruit industry in Western Australia during the 2003/2004 season was to $46.79 per tree (Collins *et al.* 2004). Since the mean number of trees per orchard was 4,446 (Table 2), the average farmgate value of the fruit per grower equates to $208,018. The loss of farmgate income due to damage by birds during the 2004/2005 season, as estimated by growers, varied widely from none to $500,000 and averaged $12,453 (Table 2). The average loss equates to 6% of average farmgate income and $1,844 per hectare.

Growers ranked Pink Lady as the most severely damaged variety, followed by Granny Smith, Sundowner and Lady Williams (Figure 2). The most commonly listed damage category was low or less than 10% and 80% of the observations were low, moderate or high (Table 3). Few were very high or extreme (Table 3).

Table 3

Number and proportion of observations of damage to fruit by birds for six categories of damage.

Category	Proportion of fruit lost (%)	Number of Observations	Proportion of observations (%)
None	0	6	3.4
Low	< 10	56	32.0
Moderate	10 – 20	43	24.6
High	20 – 40	41	23.4
Very High	40 – 70	20	11.4
Extreme	> 70	9	5.1
Total		175	100

Table 4

Labour and financial resources dedicated to control of damage to pome fruit crops by birds during the 2004/2005 season.

	Days pest control was undertaken	Hours per day	Cost per hour ($)	Total for pest control last season ($)
Median	80	2	25	3,240
Mean	82.74	2.18	29	5,041
Std. Deviation	51.03	1.94	20	7,351
s.e.	7.22	0.27	2.96	1,084
Minimum	12	0.16	1	200
Maximum	220	10.62	120	45,000
n	50	50	47	46

Damage control

A high proportion of growers (77% ± 7.9%, *n* = 78) reported that they had previously used pest control to prevent damage by Baudin's Cockatoo. On average, growers estimated that they undertook damage control on 83 days during the 2004/2005 season (Table 4). They estimated that they dedicated around two hours to damage control per day and valued this time at $29 per hour (Table 4). These figures show that growers spent an average of $5,041 on damage control per property (Table 4), which equates to $741 per hectare and represents 2% of farmgate income per property.

The most effective damage control techniques employed by growers were shooting to scare, harassment via motorcycle, harassment via motor vehicle, gas guns and explosive cartridges (Figure 3). Three growers listed shooting to kill as one of their techniques (Figure 3) in a space provided for 'other' techniques, even though this option was not listed on the survey.

Around two-thirds of growers (64% ± 11.2%, *n* = 56) reported that they had used a combination of control techniques to reduce damage by Baudin's Cockatoo. The most effective combinations of two or three techniques were: gas guns as the primary technique in combination with motor cycle (harassment) and/or shooting to scare; and motor cycle (harassment) as the primary technique, in combination with gas guns and/or shooting to scare (Table 5).

Patterns of Damage

An ANOVA model showed that the proportion of fruit damaged was not related to Shire, the size of the orchard, the number of trees in the orchard or tree density (Table 6). The proportion of fruit damaged was a function of individual property and crop variety (Table 6). Post-hoc analyses of the three most commonly grown varieties showed that damage to Pink Lady was significantly greater than damage to Fuji and Granny Smith.

Discussion

All surveys of damage to fruit by birds have advantages and limitations. Mailed surveys, such as the present one, have the advantage of low cost and wide geographic coverage, but they commonly receive lower response rates than face-to-face interviews and phone interviews (Tracey & Saunders 2003). The limited response rate of 31% to the present survey has the potential to introduce bias into the results, because it is not know if the group that responded was representative of the industry as a whole. However, this can be minimised via the prudent wording of the questions to ensure objectivity (Tracey & Saunders 2003) and by declaring error values to each question, as in this study.

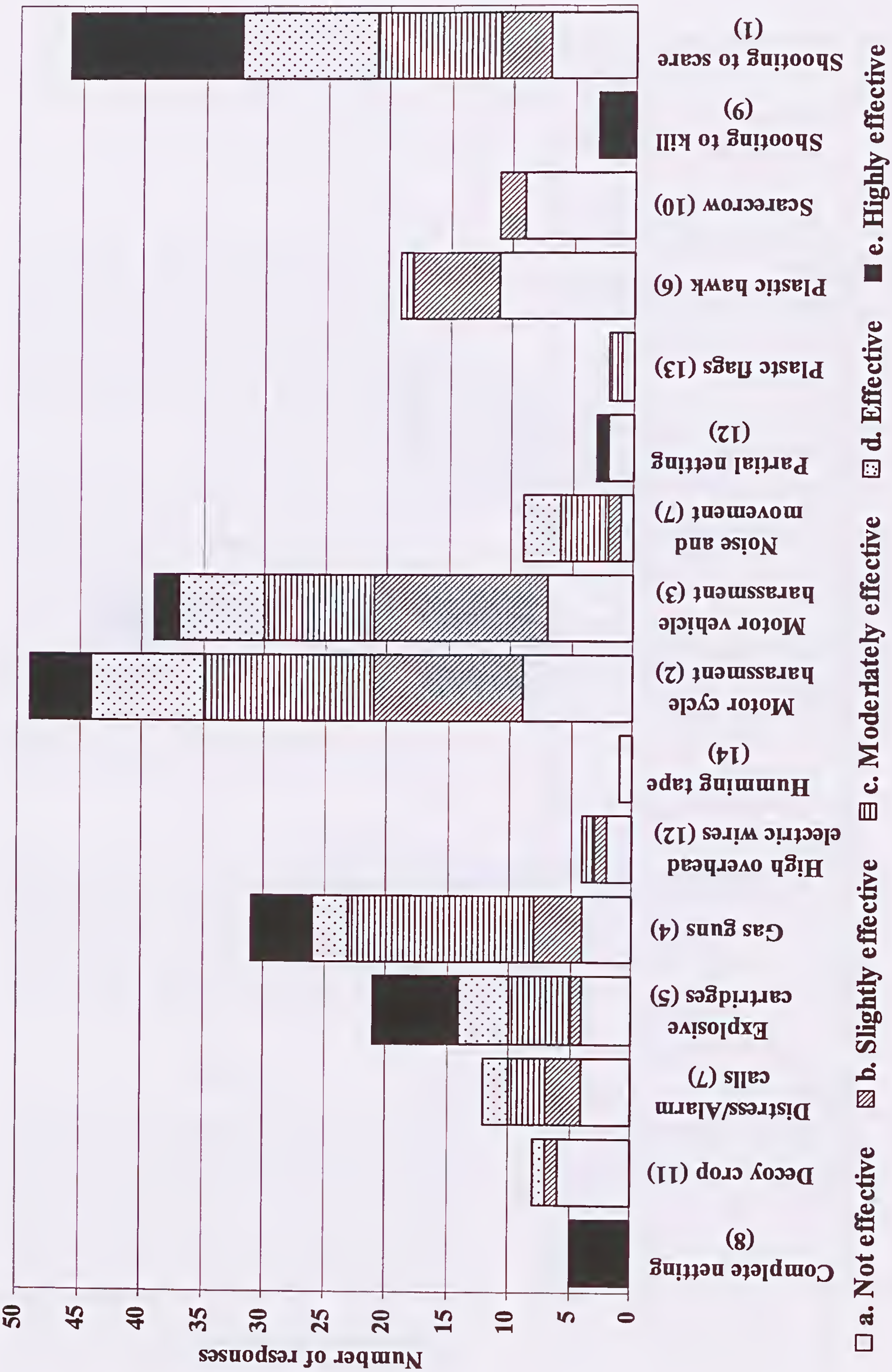

Figure 3. Control techniques for preventing damage to pome fruit by Baudin's Cockatoo (n = 263). Values in parentheses show ranking for technique by relative effectiveness of damage control.

Table 5

Combinations of techniques used to protect pome fruit crops from damage by Baudin's Cockatoo. Rank shows relative effectiveness of 1–7 from most to least effective.

Primary	Second	Third	Rank
Explosive Cartridges	Distress/Alarm calls	Motor Cycle (harassment)	6
	Gas guns	Motor Cycle (harassment)	6
Distress/Alarm calls	Motor Cycle (harassment)	Shooting to scare	7
Gas guns	Explosive Cartridges	Shooting to scare	5
"	Motor Cycle (harassment)	Motor Vehicle (harassment)	5
		Shooting to scare	1
	Shooting to scare	Motor Cycle (harassment)	3
		Motor Vehicle (harassment)	2
Motor Cycle (harassment)	Gas guns	Permanent complete netting structure	3
		Shooting to scare	1
	Motor Vehicle (harassment)	Gas guns	3
	Plastic Hawks	Shooting to scare	6
	Shooting to scare	Explosive Cartridges	3
		Gas guns	4
Motor Vehicle (harassment)	Motor Cycle (harassment)	Gas guns	5
	Shooting to scare	Partial netting	4
Plastic Hawks	Shooting to scare	Motor Cycle (harassment)	5

Table 6

Results of one-way ANOVA examining the relationship between the proportion of fruit damaged and orchard parameters. Significant values are shown in bold.

Parameter	F	d.f.	P
Individual property	6.6	18,52	**< 0.0001**
Shire	0.80	6,52	0.5810
Crop variety	3.04	6,52	**0.0015**
Planting area (ha)	0.38	1,49	0.3588
Number of trees	0.34	1,44	0.5647

Response rates to surveys of fruit damage vary widely (Lim *et al.* 1993, Graham *et al.* 1999, Tracey & Saunders 2003) and reflect monetary losses incurred by growers (Bomford & Sinclair 2002). For example, a survey of bird damage to apples, pears and cherries in the Adelaide Hills recorded response rates of up to 94%, and the proportion of responses directly reflected perceived monetary loss (Graham *et al.* 1999). Assuming the same applies to pome fruit growers in south-west Western Australia, the response rate of 31% to the present survey suggests that fruit damage and monetary loss would be unlikely to be excessive. This was reflected in the low loss of farmgate income and low proportion of fruit damage reported in the survey. The impact of the damage, however, is likely to be a function of the size of the operation i.e. even small losses may have a significant impact on small businesses.

The limited number of growers who returned the survey may also reflect the attitudes of growers toward the cockatoos and perceptions of the level of damage it causes. For example, it may be that the limited response rate reflects antagonism toward the cockatoos and the regulatory authority. The surveys in this study carried the Western Australian Fruit Growers' Association (WAFGA) logo and a Department of Environment & Conservation (DEC) staff member and fruit grower from the local catchments group encouraged growers to return the surveys by collecting them in person. I conclude, therefore, that since the level of damage for survey respondents was low on average and the response rate to the survey was also low, this issue was not a high priority for majority of growers during the 2004/2005 season.

Baudin's Cockatoo was not the only bird pest of pome fruit in Western Australia as other parrots were also nominated as damage causing species. However, this cockatoo does appear to be a common and frequent pest species in and around pome fruit orchards (Long 1985, Halse 1986), since almost all growers had previously incurred damage by Baudin's Cockatoo. Most had also incurred damage during the year leading up to the survey.

Despite the high proportion of growers who's fruit had been damaged by Baudin's Cockatoo, around a quarter of survey respondents had not attempted to prevent or minimise the damage. This suggests damage control is not justified among these growers and there may be a number of reasons for this. Large-scale growers, for example, may be prepared to concede the economic losses of damage by Baudin's Cockatoo because they have large, high value crops that are difficult (or uneconomical) to protect. Another possibility is that this group represents those who rely on shooting and so have not needed to develop a non-lethal damage control program.

Some growers suggested that non-lethal damage control techniques are not cost-effective and/or not effective for protecting pome fruit from damage by Baudin's Cockatoo. However, this view was not supported by the data collected in the survey. On average, growers spent a small proportion of their income on damage control and noise emitting devices were rated as effective or highly effective by growers. Scaring with the use of noise emitting devices, such as gas guns and explosive cartridges, was also identified as an effective deterrent in a previous study (Long *et al.* 1989).

Current best practice for the control of fruit damage by birds involves gaining an understanding of the

patterns of damage, assessing the feasibility of control options, implementing a program and monitoring its effectiveness (Braysher 1993, Sinclair 2003). The data collected in this study can be used by growers to develop an effective, efficient damage control strategy for protecting pome fruit from damage by Baudin's Cockatoo. Fruit damage varied significantly between individual properties in the survey and this has also been observed during previous studies (Long 1985). This may be due to a number of factors, such as the variety of fruit grown, proximity to nature reserves, topography and the damage control program employed on individual properties.

One of the key factors accounting for the variation in damage levels appears to be the variety of fruit grown. Pink lady apples were the most commonly and severely damaged fruit variety in this study and a previous study (Halse 1986). Thus, wherever possible, it would be prudent for that all commercial pink lady growers to plan a non-lethal damage control program to protect fruit. Scaring techniques are likely to be effective for preventing fruit damage if used in accordance with current best practice guidelines (Chapman & Massam 2005a, Government of Western Australia 2005). This study showed that combinations of shooting to scare (including explosive cartridges), harassment via motorcycles and gas guns are effective means of reducing damage to pome fruit by Baudin's Cockatoo.

Shooting of Baudin's Cockatoo to protect pome fruit in commercial orchards is unlawful and can-not justified in terms of the damage the cockatoos cause or the costs of damage control to growers. DEC has a legislative responsibility to protect Baudin's Cockatoo from threatening processes and thus, aims to eliminate illegal shooting. WAFGA aims to produce fruit in a sustainable manner and this should apply not only to the use of resources, such as water, but also to the conservation of biodiversity. The use of non-lethal scaring techniques to protect pome fruit from damage by the endangered Baudin's Cockatoo is shown here to be an effective strategy to meet WAFGA's sustainability objectives.

Although most growers who responded to the survey were aware that it is an endangered species, fewer than half agreed that Baudin's Cockatoo should be protected and many called for the cockatoos to be culled in the comments section of the survey. This highlights the need for a strategy to inform growers of why this species is listed as endangered and to demonstrate the extent to which killing the birds to protect fruit threatens the species. An education strategy has now been developed by DEC as part of the recovery program (*e.g.* Chapman & Massam 2005b, Government of Western Australia 2005) and the effectiveness of this strategy will be assessed by DEC as part of the recovery program.

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The rediscovery of *Eucalyptus nutans* F. Muell. from the south coast of Western Australia

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Abstract

Eucalyptus nutans F. Muell. (Myrtaceae) has been re-discovered after being misidentified and lost for more than a century. It was first collected in 1862 from near Bremer Bay on the south coast of Western Australia by George Maxwell and subsequently described by Ferdinand von Mueller in 1863. It was recollected by Herbert Demarz in 1973 and 1979, and cultivated at Kings Park and Botanic Garden, though not recognised as the long-lost typical *E. nutans* until our research reported herein. Although somewhat well known in cultivation, it is rare in nature and in need of *ex situ* conservation. The reserve on which it occurs is recommended to be added to Fitzgerald River National Park.

Kewords: Bremer Bay, *Eucalyptus cernua*, horticulture, Moort, conservation

Introduction

Despite increasing interest in eucalypts by botanists, and for their utilisation in forestry, ornamental horticulture, landscape plantings and bushland restoration, significant taxonomic issues remain to be resolved, especially in Western Australia. This applies even for some of the best known and most widely used ornamental mallees. Even new species of forest trees have remained obscure to science until recently (e.g. Hopper & Wardell-Johnson 2004).

Here, we report a case of misapplication of a name in wide use for more than a century, and of the rediscovery of the true identity of what was believed to be a well-known southwest-eucalypt.

The Noongar Aboriginal people knew the small, round leaved, spreading, non-lignotuberous trees from the south coast and nearby inland areas collectively as the "moorts". Brooker & Hopper (2002) applied the other Noongar term "marlock" to this group of eucalypts as a way of standardising the name for those that occur as "more or less pure stands of short, erect, thin-stemmed 'trees', that do not produce lignotubers". Both names are therefore accepted as the common name of the members of the group of predominantly Western Australian south coast endemic eucalypts that includes *Eucalyptus cernua* Brooker & Hopper, *E. platypus* Hook. subsp. *platypus, E. platypus* subsp. *congregata* Brooker & Hopper, *E. nutans, E. utilis* Brooker & Hopper and *E. vesiculosa* Brooker & Hopper.

Eucalyptus nutans was described by Ferdinand von Mueller (1863) from material collected by George Maxwell near Bremer Bay in southern Western Australia (Fig. 1). Previously *Eucalyptus platypus* was described in 1851 from material collected near King George's Sound. Around a century and a half later, Brooker and Hopper (2002) published the names *Eucalyptus platypus* subsp. *congregata, E. cernua* and *E. vesiculosa.*

Eucalyptus nutans was thought for many years to have been the same red-flowered moort collected near Ravensthorpe now known to be *Eucalyptus cernua*. The circumscription of the latter species then also included the more-recently recognised mallee taxon *E. proxima* Nicolle & Brooker (2005). Brooker & Hopper (2002), when naming the Ravensthorpe district mallets as *E. cernua,* indicated that the type of *E. nutans* was a variant of *E. platypus* but at the time they had not seen *E. nutans* in the field near Bremer Bay.

Previously, Herbert Demarz, Kings Park and Botanic Garden seed collector from 1968 to 1989, collected near Bremer Bay in 1973 and 1979 a red-flowered tree believed at the time to be *Eucalyptus platypus.* Three trees from seed from these collections were planted and persist in the parkland of the LotteryWest Family Area at Hale Oval in Kings Park and Botanic Garden. In 1992, one of us (N McQ) collected a red-flowered eucalypt near Bremer Bay which matched these plantings.

Further investigations in the field near Bremer Bay during 1999 to 2003, including a joint trip in 2003, convinced us that this was likely to be the type site of von Mueller's *Eucalyptus nutans,* and that the species was indeed distinct from *E. platypus* (Table 1, Fig. 2)

Figure 1. Holotype of *E. nutans* (photograph by National Herbarium of Victoria) Reproduced with permission from the State Botanical Collection, National Herbarium of Victoria (MEL).

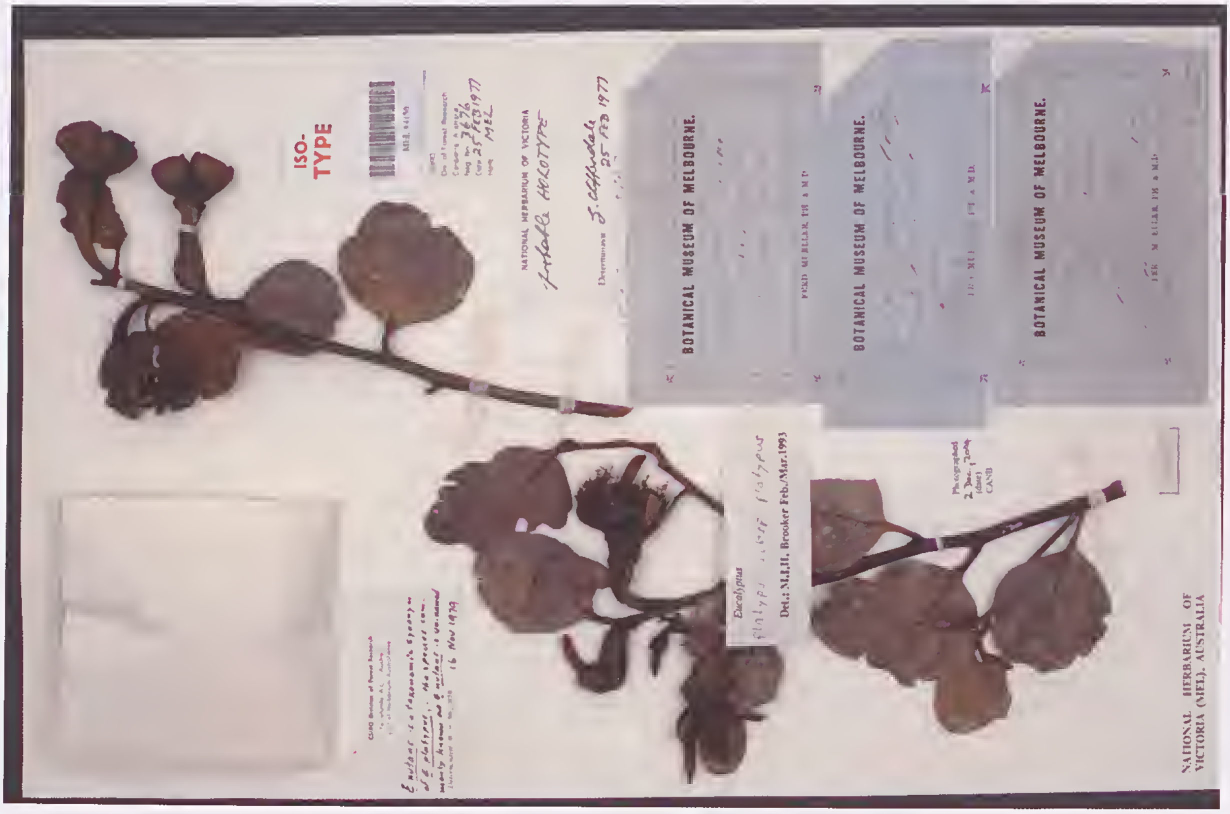

Figure 2. Isotype of *E. nutans* (photograph by National Herbarium of Victoria). Reproduced with permission from the State Botanical Collection, National Herbarium of Victoria (MEL).

Figure 3. Buds and fruits of *E. platypus* subsp. *platypus* Pt Ann and *E. nutans* (photo N. McQuoid).

Figure 4. Buds, flowers and fruit of *E. nutans* in hand of Bremer Bay Identity Priscilla Broadbent (photo N. McQuoid).

Figure 5. Buds, flowers and fruit of *E. nutans* November 2006 (Photo N. McQuoid).

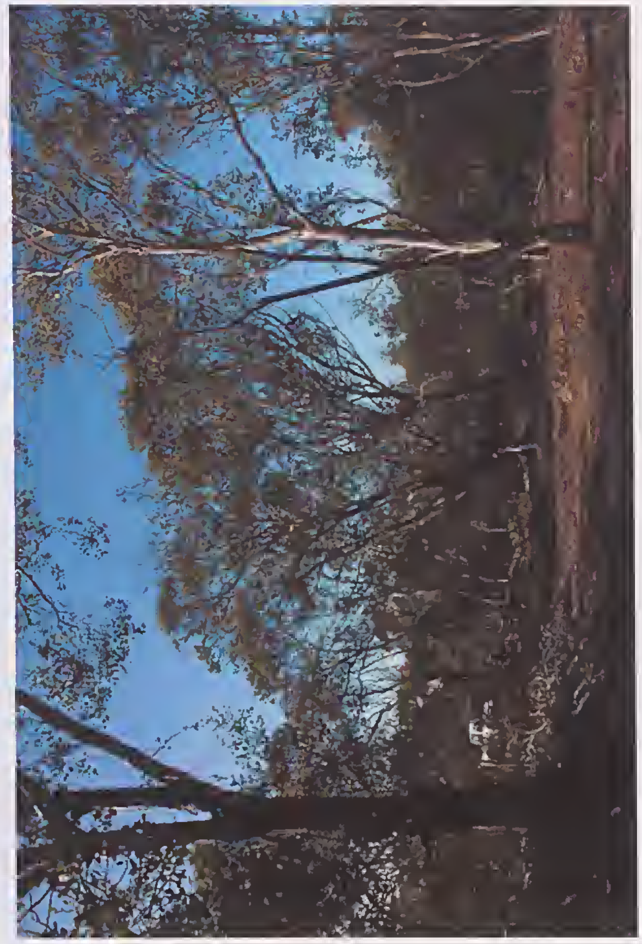

Figure 6. Ten metre tall grove of very old *E. nutans* with Bremer Bay identity Don Scott providing a 1.9 metre scale (photo N McQuoid).

Eucalyptus nutans F. Muell. Fragm. 3:152 (1863). Type: Bremer Bay, December 1862, *G Maxwell s.n.* Holo: MEL 84155! Iso MEL 84156!

E. platypus var. *nutans* (F. Muell.) Benth., Fl. Austral. 3: 235 (1867)

Erect marlock or moort to 10 metres, non-lignotuberous, killed by fire; leaves dark green, petiolate, thick, glossy, ovate to orbicular, (52-) 63 (-73) x (33-) 43 (-50)mm; peduncle broad, long, strap-like, down-curved to pendulous, (35-) 55 (-66) x (9-) 14 (-18)mm; buds obtusely conical, slightly warty, narrower than the hypanthium, (8-) 10 (-11)mm x 3.5mm; stamens red (rarely cream); fruit sessile, cupular to obconical, 4 winged, rim narrow, descending, valves 5 in a distinct wheel-like arrangement; seed black, compressed obovoid to ovoid, 1 – 1.75 x .75 – 1mm. (Figs 1, 2 and 3)

Affinities

Eucalyptus nutans is in the *Eucalyptus* sect. *Bisectae* Maiden ex Brooker, subsect. *Glandulosae* Brooker, ser. *Erectae* Brooker, and suprasp. *Latae* Brooker (Brooker 2000). It has erect stamens and shares many characteristics with the other members of the *E.* suprasp. *Latae* (i.e. *Eucalyptus utilis, E. platypus* subsp. *platypus* and *E. platypus* subsp. *congregata*). It differs by its shorter operculum, more robust and winged fruit with a wider disc and more prominent valves; its wider, longer and often curled peduncles; its larger round green leaves; its taller stature; and its almost exclusively red flowers (two plants at the type and only known location have cream flowers).

Specimens examined

(Precise location withheld). WESTERN AUSTRALIA: Bremer Bay, Feb 1973, *H Demarz 4293* (KPBG); Bremer Bay, 20 November 1979, *H. Demarz 7830* (KPBG); Bremer Bay, 9 August 1992, *N McQuoid NKM 309* (CANB); Bremer Bay, 30 December 2002.

Figure 7. Seven metre tall trees of *E. nutans* near Bremer Bay with Bremer Bay identity Don Scott providing a 1.9 m scale (photo N. McQuoid).

Table 1

Comparison of key morphological features between *Eucalyptus nutans* and *E. platypus subsp. platypus*

	Adult leaves	Peduncle	Fruit	Operculum
Eucalyptus nutans (Bremer Bay)	Ovate to orbicular, glossy dark green, petiolate, (52-) 63 (-73)mm long x (33-) 43 (-50) mm wide	Broad, long, strap-like, down-curved to pendulous, (35-) 55 (-66) mm long x (9-) 14 (-18)mm wide	Sessile, cupular to obconical, 4 winged, rim narrow, descending, valves 5 in a distinct wheel-like arrangement (17-) 22 (-29)mm long x (13-) 16 (-20) mm wide	Obtusely conical, slightly warty, (9-) 12 (-15)mm long x 4 – 5mm wide
Eucalyptus platypus subsp. *platypus* (Pt Ann, Fitzgerald River National Park)	Obovate to orbicular, petiolate, glossy mid to dark green, (36-) 45 (-64)mm long x (34-) 40 (-48) mm wide	Broad, erect to slightly down-curved, (40-) 42 (-53)mm long x (9-) 11 (-13)mm wide	Sessile to very slightly pedicellate, slightly 4 winged, obconical to barrel shaped, rim thick, disc level to slightly ascending, valves 4, to rim level or slightly exserted (17-) 19 (-22)mm long x (12-) 15 (-18)mm wide	Horn shaped, smooth, (13-) 18 (-21)mm long x 4 mm wide

Measurements show range in brackets either side of average

Distribution and habitat

Known from a single population near Bremer Bay on the south coast of Western Australia. Occurs on gravelly clay over spongolite marine sediments on an unvested reserve adjacent to Fitzgerald River National Park. It grows in a more or less pure stand with *Acacia glaucoptera, A. cyclops, Hakea laurina, Eucalyptus anceps, E. occidentalis, Rhadinothamnus rudis, Lepidosperma sp, Astroloma sp.*

Flowering period

November to April

Common name

Eucalyptus nutans F. Muell. is known locally by the common names Bremer or red-flowering moort.

Conservation status

Recommended for listing as Declared Rare Flora (DRF) under the Department of Environment and Conservation of WA (DEC) conservation codes. The type site of *Eucalyptus nutans* is its only known location where it occurs as several thousand plants over a few hectares. The population is in three age classes of eight very old ten-metre tall trees adjacent to a stand of younger six-to-seven metre tall trees, with both surrounded by a 21 year-old four-metre tall thicket where a 1995 fire burnt the majority of the population. It hybridises here with *Eucalyptus occidentalis.* It is rare in nature, and more commonly known as cultivated plants in gravel pits east of Albany and at Kings Park.

The only known site is not in the current conservation estate and searches in the Fitzgerald Biosphere area have failed to find it elsewhere

Despite its small area of natural occurrence, *E. nutans* grows well in cultivation at Kings Park and Botanic Garden, and was apparently planted by the late Spike Daniels in gravel pits as a rehabilitation species seventy to one hundred kilometres east and north-east of Albany. *Ex situ* conservation by growing it in landcare and ornamental horticulture plantings on suitable soils in the Bremer Bay area would be beneficial to its long term survival

The CALM South Coast Management Plan 1992 – 2002 (Anon 1991) recommends that the two unvested reserves where, and adjacent to where, *Eucalyptus nutans* occurs should be included into Fitzgerald River National Park. Implementing this recommendation would improve its conservation status.

Notes

The story of *E. nutans* illustrates the fundamental importance of rigorous and accurately applied systematics research to successful conservation of biodiversity. Typical *E. nutans*, a rare and highly-localized endemic species vulnerable to extinction through frequent fires, remained obscure and uncollected for 130 years, with its name incorrectly applied to an undescribed mallet (*E. cernua*). Because of its vulnerability to fire, *E. nutans* may well have been rendered extinct in the future, had it not been recognised as different and worthy of investigation by Demarz, Daniels and ourselves.

In this regard, there are many other parallels applying to the southwest flora, where fully a third of the 8000 currently recognised species have only been described since the 1960s, and some 14% remain without a formal scientific description (Hopper and Gioia 2004). Countless cases also exist, as here, of species complexes needing careful attention to the circumscription of taxa already named. With taxonomy still in need of elucidation for eucalypts, among the largest and better known of plant groups in the flora, systematic research backed up by field surveys deserves ongoing attention.

Acknowledgements: We are grateful to the late Herbert Demarz, Kings Park and Botanic Garden Seed Collector, 1968 – 1989, who collected this taxon near Bremer Bay in the 1970's, and the late Spike Daniels for noticing and growing this taxon. Luke Sweedman, Seed Collector, Botanic Gardens and Parks Authority, alerted us to Herbert Demarz's collection. Marion Blackwell pointed out the presence of cultivated plants in Kings Park and Botanic Garden. Grady Brand Curator, Botanic Garden, Botanic Gardens and Parks Authority, offered comments on this taxon growing at Kings Park. Brendan Lepschi and John Connors of CANB provided access to information in their collection. Dean Nicolle was helpful in discussions regarding the taxonomic status of *E. nutans.* Assistance in the photography of the Holotype and Isotype of E. nutans was provided by staff of the National Herbarium of Victoria (MEL), Royal Botanic Gardens Melbourne, and the Australian National Herbarium (CANB), and this is gratefully acknowledged. The funding by the South Coast Regional Initiative Planning Team (SCRIPT) for the Ecosystem Support Project through the WA and Australian Governments also is gratefully acknowledged.

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